Realization and Evaluation of an Aircraft Onboard Retrofit Trajectory Management System

Vom Fachbereich Maschinenbau
an der Technischen Universität Darmstadt
zur
Erlangung des Grades eines Doktor-Ingenieurs (Dr.-Ing.)
genehmigte

Dissertation

vorgelegt von

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Tag der Einreichung:	30.06.2014
Tag der mündlichen Prüfung:	11.11.2014

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Dedicated to my Grandmother Marianne Kirchner,
who fostered my interest in science and higher education.

Zusammenfassung

Der Luftverkehr wird als Folge der zunehmenden Globalisierung in den nächsten Jahren signifikant wachsen. Zur Bewältigung dieses zusätzlichen Verkehrsaufkommens suchen die beteiligten Entscheidungsträger nach neuen Verfahren für das *Luftverkehrsmanagement*. *Trajektorien basierte Operationen* stellen dabei ein solches neuartiges Verfahren dar. Durch das Teilen einer detaillierten Trajektorie zwischen den involvierten Entscheidungsträgern des *Luftverkehrsmanagement-Prozesses*, wird es möglich den *Luftverkehrsfluss* mittels einer präziseren Planung zu optimieren. Eine Herausforderung ist dabei der Übergang von heutigen Verfahren hin zu *Trajektorien basierten Operationen*. Des Weiteren stellen die Ausrüstungskosten für Technologien zur Unterstützung der neuen Verfahren, eine Hürde dar. Hierbei kann eine Ausrüstung entweder durch Regulierung verpflichtend vorgeschrieben werden, oder die Kosten amortisieren sich auf Grund gewonnener Effizienzsteigerungen über einen gewissen Nutzungszeitraum. Dabei gilt: je höher die Ausrüstungsrate von Flugzeugen mit *Trajektorien-Management-Systemen* ist, umso höher werden die Vorteile durch die Verwendung von *Trajektorien basierten Operationen* ausfallen.

Diese Dissertation ist eine Machbarkeitsstudie für ein flugzeugseitig nachrüstbares *Trajektorien-Management-System*. Das System zielt auf eine kosteneffiziente Einrüstung in Flugzeuge, um einen möglichst hohen Ausrüstungsgrad zu erreichen. Dabei ist das *Trajektorien-Management-System* als *Entscheidungsunterstützungssystem* für den Piloten ausgelegt, welcher weiterhin der Entscheidungsträger an Bord des Flugzeuges ist.

Es werden zunächst die zu erwartenden Änderungen des *Luftverkehrsmanagement-Systems* und flugzeugseitiger Technologien in Bezug auf die Einführung von *Trajektorien basierten Operationen* analysiert. Zur Gestaltung der Mensch-Maschine Schnittstelle für den Piloten werden Grundlagen der Ingenieurpsychologie betrachtet. Das *Trajektorien-Management-System* soll dabei die Funktionen der *Trajektorien Verhandlung, Überwachung und Führung* ermöglichen. Die *Trajektorien Verhandlungsfunktion* ermöglicht den Austausch von Trajektorieninformationen zwischen den beteiligten Entscheidungsträgern am Boden und in der Luft. Um Piloten die *Trajektorien Überwachung* eines zeitlich beschränkten Wegpunktes zu erleichtern, wurde dieser in eine longitudinale Ausdehnung entlang der Route transformiert. Für die Betrachtung der zeitlichen *Trajektorien Führung* in die bestehenden Kaskaden der Flugzeugregelung wurden vier Integrationen realisiert.

Evaluierungen des realisierten *Trajektorien-Management-Systems* fanden in dem Forschungssimulator der Technischen Universität Darmstadt, an Bord des 2012 Boeing ecoDemonstrator, sowie an Bord des Advanced Technology Research Aircraft vom Deutschen Zentrum für Luft und Raumfahrt statt. In den Simulatorversuchen wurde der Fokus auf eine Analyse der Gebrauchstauglichkeit des Systems gelegt. Das Briefing und die *Trajektorien Überwachung* mit Hilfe des realisierten *Trajektorien-Management-Systems* wurden mit einer Integration in das bestehende *Flugzeugmanagementsystem* verglichen. Die Boeing ecoDemonstrator Versuche zielten auf eine Evaluierung der *Trajektorien Führungsfunktion* im Anflug. Auf Grund eines Kommunikationsfehlers konnte die Trajektorie nicht zwischen den am Boden und in der Luft beteiligten Entscheidungsträgern

verhandelt werden. Dies zeigt wie anfällig die umgesetzten Verfahren gegenüber Kommunikationsfehlern sind. An Bord des ADVANCED TECHNOLOGY RESEARCH AIRCRAFT wurde die Anwendbarkeit des realisierten *Trajektorien-Management-Systems* vom Flugsteig des Abflughafen zum Ankunftsflugsteig evaluiert.

Obwohl die realisierten *Trajektorien Führungssysteme* die geforderten Genauigkeiten erfüllen konnten, wird eine Umsetzung auf Grund der erhöhten Arbeitsbelastung der Piloten nicht empfohlen. Hingegen stellt für die Probanden die Einbindung des *Trajektorien-Management-Systems* als grafische Aufbereitung der *Trajektorien Verhandlung* und *Überwachung*, potentiell mit einer bidirektionalen Anbindung an das das *Flugzeugmanagementsystem*, einen subjektiven Mehrwert dar.

Abstract

Air traffic will grow significantly in the future, as a consequence of increasing globalization. To cope with additional traffic, both in the air and on the ground, stakeholders look to new *Air Traffic Management* procedures unburden the system, and Trajectory-Based Operations are the key to accomplishing this goal. By sharing a detailed trajectory between all *Air Traffic Management* participants, *Trajectory-Based Operations* promise more precise planning to accommodate demand and optimize all aspects of air traffic flow. However, transitioning from current operations to *Trajectory-Based Operations* is most challenging when considering the transition phase of this implementation. *Trajectory-Based Operations* require new technologies, and the perceived investment required for those technologies may, at first, appear to be a hurdle - perhaps an impediment to doing so. This implementation can either be mandated through regulation or by budgeting for and limiting investment costs. The higher the equipage rate with *Trajectory Management Systems*, the higher will be the benefits realized through the use of *Trajectory-Based Operations*.

This thesis provides a proof-of-concept for an onboard retrofit *Trajectory Management System* that enables a cost-efficient implementation resulting potentially in a high equipage rate. For this research, the *Trajectory Management System* is designed as decision support system for the pilot who is the chief decision maker onboard the aircraft. To support this proof-of-concept, this research involved a close analysis of the expected changes to the *Air Traffic Management* system with regard to *Trajectory-Based Operations*. Cognitive ergonomics were reviewed, determining the best integration of *Trajectory-Based Operations* into an *Electronic Flight Bag* charting application to support trajectory negotiation, monitoring, and guidance. The negotiation functionality would permit the exchange of trajectories between all on-ground and aboard-flight stakeholders. Trajectory monitoring would transform the temporal constraint of a waypoint into a longitudinal area along the planned route. Four guidance principles are considered that represent differing integrations of the temporal guidance into the aircraft control loops.

Evaluations using flight simulator at Technische Universität Darmstadt, onboard the 2012 Boeing *ecoDemonstrator*, and the Deutsches Zentrum für Luft- und Raumfahrt *Advanced Technology Research Aircraft*, demonstrated the general feasibility of the *Trajectory Management System* under real world conditions. In the simulator trials, the focus was on the usability of the system. The briefing and monitoring of a trajectory using the charting application was compared to integration into the aircraft *Flight Management System*. The *ecoDemonstrator* trials, focusing on an arrival integration of the trajectory, showed that the system is prone to communication failure, which led to an increased initial time deviation from the planned trajectory. In the German flight trials, the applicability of the *Trajectory Management System* was evaluated.

Although the evaluated *Trajectory Guidance* functions have met the required accuracy, an integration is not recommended because of increased pilot workload. Instead the evaluating pilots found subjective benefits of a *Trajectory Management System* for the graphical *Trajectory Negotiation* and *Monitoring*, possibly with a bidirectional *Flight Management System* integration.

Acknowledgements

This dissertation was written during my time as research associate at the Institute of Flight Systems and Automatic Control of the TU Darmstadt, in a close cooperation with JEPPESEN. First and foremost I thank Prof. Dr.-Ing. Uwe KLINGAUF, head of the Institute, for giving me the chance and the freedom to perform the research presented in this thesis. I thank Prof. Dr.-Ing. Dirk KÜGLER, of the Institute of Flight Guidance from the DEUTSCHES ZENTRUM FÜR LUFT- UND RAUMFAHRT E.V. (DLR) to serve as second examiner for this thesis. For mentoring this dissertation and me as a person, I thank Dr.-Ing. Jens SCHIEFELE from JEPPESEN.

My colleagues at the Institute I thank for the reviews, discussions and help. Christoph SANTEL and Paul HAIDUK especially for their support on human factors related topics and my "roommates" Esther HOHBERGER and Katja HEIN for the distractions and the memorable time at the institute.

Research results in science are never achieved by one person but are the gained by a team working towards a common goal. Therefore, I thank the partners at JEPPESEN, the DLR and at BOEING RESEARCH AND TECHNOLOGY EUROPE (BRTE) for their efforts especially in the performed flight trials.

Dr.-Ing. Niels STARK, Dr.-Ing. Nima BARRACI, and Dr.-Ing. Andreas SINDLINGER of the JEPPESEN office in Neu-Isenburg, I thank for their support, guidance, feedback and help. Kai GIESE, Hayung BECKER, and Dr.-Ing. Bernd KORN of the DLR, I thank for their support during the integration and the long nights in the DLR simulator. Ramon GOMEZ LEDESMA, PhD and David GARRIDO-LOPEZ, PhD of BRTE, I thank for their support towards the ecoDemonstrator flight trials. I thank the JEPPESEN Gdansk office especially: Michal NARWOJSZ, Zbigniew NASTALSKI, Lukasz STANKIEWICZ, Krzysztof PYTEL, and Witek ZAMORSKI for their implementation support in preperation of the flight trials.

For her thorough editing to make the reading of this thesis a more pleasant experience, I thank Maura BETLER. My student Stefan NEIS, I thank for his support on the ecoDemonstrator flights.

Last but not least, I thank my parents, Joachim and Katrin WESTPHAL, for their love and support raising me up and my fiance Natalja BALKOWSKI for her patience during the execution of the thesis.

Contents

Symbols and Abbreviations

Symbols

ΔC_D	Difference of drag coefficient over configurations	[s]
Δh	Difference of height	[m]
Δs	Difference of stretches	[NM]
Δt	Difference of times	[s]
ΔT	Temperature difference to ISA	[K]
Δt_{flaps}	Difference of flaps extension time	[s]
ϵ_{min}	Minimum glide ratio	[-]
η	Thrust-specific fuel flow	$[\frac{\mathrm{kg}}{\mathrm{min \cdot kN}}]$
κ	Adiabatic index	[-]
λ	Latitude	[°]
μ	Mean	[-]
ϕ	Longitude	[°]
ρ	Air density	$[\frac{\mathrm{kg}}{\mathrm{m}^2}]$
ρ_0	Sea level standard atmospheric air density	$[\frac{\mathrm{kg}}{\mathrm{m}^2}]$
σ	Standard deviation	[-]
$\vec{V}$	Velocity vector	[kts]
$\vec{V}_{cr,CI_{min/max}}$	Minimum/Maximum cruise speed vector from CI	[kts]
$\vec{V}_{cr,min/max}$	Minimum/Maximum cruise speed vector	[kts]
$\vec{V}_{current}$	Current speed vector	[kts]
$\vec{V}_{maxthrust}$	Maximum thrust speed vector	[kts]
$\vec{V}_{min,cr}$	Minimum cruising speed vector	[kts]
$\vec{V}_{min,stall}$	Minimum stall speed vector (BADA)	[kts]
$\vec{V}_{MO}$	Maximum operating speed vector (BADA)	[kts]
$\vec{V}_{MRC}$	Maximum range cruise speed vector	[kts]
$\vec{V}_{planned}$	Planned speed vector	[kts]
$\vec{V}_{stall}$	Stall speed vector (BADA)	[kts]
$\vec{V}_{wind}$	Wind speed vector	[kts]
C_D	Drag coefficient	[-]
C_{D0}	Parasitic drag coefficient (BADA)	[-]
C_{D2}	Induced drag coefficient (BADA)	[-]

C_{f1}, C_{f2}	Thrust-specific fuel consumption coefficients (BADA)	$[\frac{\text{kg}}{\text{min}\cdot\text{kN}\cdot\text{kts}}]$
C_{fcr}	Cruise fuel flow correction coefficient (BADA)	[-]
C_{Fuel}	Fuel-specific costs	$[\frac{\$}{\text{kg}}]$
C_L	Lift coefficient	[-]
$C_{Lbo(M=0)}$	Buffet onset lift coefficient (BADA)	[-]
$C_{Tc,1}, C_{Tc,2}, C_{Tc,3}$	Maximum climb thrust coefficients (BADA)	[N],[ft],$[\frac{1}{\text{ft}^2}]$
$C_{Tc,4}, C_{Tc,5}$	Thrust temperature coefficients (BADA)	[K],$[\frac{1}{\text{K}}]$
C_{Time}	Time-specific costs	$[\frac{\$}{\text{min}}]$
$C_{V_{min}}$	Minimum safety limit from stall speed (BADA)	[-]
CAS_{cmd}	Commanded calibrated airspeed	[kts]
CI	Cost index	$[\frac{kg}{\text{min}}]$
d	Distance	[NM]
D	Drag	[N]
$d_{TCP_{constraint}}$	Distance to next constrained TCP	[NM]
$d_{TCP_{n/m}}$	Distance to TCP n/m	[NM]
$f_{cr,CI=xx}$	Fuel flow in cruise at CI=xx	[K]
f_{cr}	Fuel flow in cruise	[K]
g	Gravitational acceleration	$[\frac{\text{m}}{\text{s}^2}]$
GS	Ground speed	[kts]
GS_{cmd}	Commanded ground speed	[kts]
h	Height	[ft]
$h_{current}$	Current height	[ft]
H_p	Pressure altitude	[ft]
$h_{planned}$	Planned height	[ft]
K	Buffeting gradient (BADA)	[-]
M	Mach number	[-]
m	Aircraft mass	[kg]
M_{bo}	Buffeting onset Mach number (BADA)	[-]
M_{cmd}	Commanded Mach number	[kts]
M_{ECON}	Minimum cost Mach number	[-]
M_{LRC}	Long range cruise Mach number	[-]
M_{MO}	Maximum operating Mach number (BADA)	[-]
M_{MRC}	Maximum range cruise Mach number (BADA)	[-]
p	Pressure	[Pa]
p_0	Sea level standard atmospheric pressure	[Pa]
R	Ideal gas constant	$[\frac{\text{J}}{\text{mol}\cdot\text{K}}]$
S	Reference wing area surface	[m^2]
s	Stretch	[NM]
$s_{min/max,envelope/CI}$	Minimum/Maximum stretch from envelope/CI speed	[NM]
t	Time	[s]

T	Temperature	[K]
$t_{constraint}$	Time constraint	[s]
$t_{current}$	Current time	[s]
$t_{TCP_{n/m,min/max}}$	Minimum/Maximum time at TCP n/m	[s]
THR	Thrust	[N]
$THR_{max,cr}$	Maximum thrust in cruise	[N]
THR_{MRC}	Maximum range cruise thrust	[N]
$X_{1,2}$	Substituted for V^2	$[\frac{m^2}{s^2}]$

Abbreviations

07MT	Glasgow Industrial Airport, MT, ICAO-Code
4DCo-GC	4D Contract - Guidance and Control
4DTRAD	4D Trajectory Data Link
A-CDA	Advanced - Continuous Descent Approach
AC	Advisory Circular
ACARS	Aircraft Communications Addressing and Reporting System
ACSS	Aviation Communication & Surveillance Systems
ADIRS	Air Data Inertial Reference System
ADS-A	Automatic Dependent Surveillance - Addressed
ADS-B	Automatic Dependent Surveillance - Broadcast
ADS-C	Automatic Dependent Surveillance - Contract
AFDS	Autopilot Flight Director System
AFM	Aircraft Flight Manual
AGL	Above Ground Level
AIDL	Aircraft Intent Description Language
AMM	Airport Moving Map
ANP	Actual Navigation Performance
ANSP	Air Navigation Service Provider
AOC	Airline Operations Center
ARINC	Aeronautical Radio Incorporated
ARTCC	Air Route Traffic Control Center
ASAS	Airborne Separation Assurance System
ASHTAM	Notice to Airmen on volcanic ash activities
ATC	Air Traffic Control
ATCO	Air Traffic Control Officer
ATCSCC	Air Traffic Control System Command Center
ATFCM	Air Traffic Flow and Capacity Management
ATFM	Air Traffic Flow Management
ATM	Air Traffic Management

ATN	Aeronautical Telecommunication Network
ATPL	Airline Transport Pilot License
ATRA	Advanced Technology Research Aircraft
ATS	Air Traffic Service
ATSU	Air Traffic Services Unit
ATTAS	Advanced Technologies Testing Aircraft System
BADA	Base of Aircraft Data
BDT	Business Development Trajectory
BOBCAT	Bay of Bengal Cooperative Air Traffic Flow Management System
BRTE	Boeing Research and Technology Europe
C-ATM	Collaborative - Air Traffic Management
CAS	Calibrated Airspeed
CASSIS	CTA/ATC System Integration Studies
CATS	Contract-based Air Transportation System
CDA-MP	Continuous Descent Approach for Maximum Predictability
CDA	Continuous Descent Approach
CDM	Collaborative Decision Making
CDTI	Cockpit Display of Traffic Information
CDU	Control Display Unit
CES	Constraint Editing System
CFIT	Controlled Flight into Terrain
CFMU	Central Flow Management Unit
CFR	Code of Federal Regulations
CI	Cost Index
CMU	Communication Management Unit
CNS	Communications, Navigation and Surveillance
ConOps	Concept of Operations
CoO	Contract of Objectives
COTS	Commercial off-the-shelf
CPDLC	Controller-Pilot Data Link Communications
CPT	Captain
CTA	Controlled Time of Arrival
CTOT	Calculated Take-off Time
DCDU	Data link Control and Display Unit
DLE	Leine, VOR
DLR	Deutsches Zentrum für Luft- und Raumfahrt e.V.
DTW	Departure Tolerance Window
EASA	European Aviation Safety Agency
ECAM	Electronic Centralized Aircraft Monitor
ECCF	ECON Cruise Cost Function
ECON	Minimum Cost Speed

EDCT	Estimated Departure Clearance Times
EDDF	Frankfurt am Main, Germany, ICAO-Code
EDDV	Hannover-Langenhagen, Germany, ICAO-Code
EDVE	Braunschweig-Wolfsburg, Germany, ICAO-Code
EFB	Electronic Flight Bag
EFF	Electronic Flight Folder
EFIS	Electronic Flight Instrument System
EGM-96	Earth Gravitational Model - 1996
ETA	Estimate Time of Arrival
ETFMS	Enhanced Tactical Flow Management System
EUROCONTROL	European Organisation for the Safety of Air Navigation
FAA	Federal Aviation Administration
FAB	Functional Airspace Block
FAF	Final Approach Fix
FANS	Future Air Navigation System
FBW	Fly-By-Wire
FCC	Federal Communications Commission
FCU	Flight Control Unit
FIR	Flight Information Region
FL	Flight Level
FMS	Flight Management System
FO	First Officer
FOM	Flight Operating Manual
G2G	Gate-to-Gate
GE	General Electric
GECO	Generic Experimental Cockpit Simulator
GGW	Glasgow MT, VOR
GNSS	Global Navigation Satellite System
GPS	Global Positioning System
GS	Ground Speed
GTF	Great Falls MT, VOR
HETEREX	Heterogeneous complex air traffic
HF	High Frequency
HITL	Human-in-the-Loop
HMI	Human Machine Interface
HP	Hewlett Packard
HVR	Havre MT, VOR
I-4D	Initial 4D
IAF	Initial Approach Fix
IAS	Indicated Airspeed
IATA	International Air Transport Association

ICAO	International Civil Aviation Organization
IEEE	Institute of Electrical and Electronics Engineers
IF	Intermediate Fix
IFPS	Integrated Initial Flight Plan Processing System
IFR	Instrument Flight Rules
ILS	Instrument Landing System
IPT	Integrated Product Team
IRS	Inertial Reference System
ISA	International Standard Atmosphere
JSON	JavaScript Object Notation
KPA	Key Performance Area
KRNO	Reno-Tahoe International Airport, NV, ICAO code
LBSF	Sofia, Bulgaria, ICAO-Code
LEPA	Palma de Mallorca, Spain, ICAO-Code
LFMM	Marseille, ICAO-Code
LHCC	Budapest, ICAO-Code
LNAV	Lateral Navigation
LuFo	Luftfahrtforschungsprogramm
MABA-MABA	Men Are Better At - Machines Are Better At
MAPt	Missed Approach Point
MCDU	Multifunctional Control and Display Unit
MCP	Mode Control Panel
MD	McDonnell Douglas
MEL	Minimum Equipment List
MIT	Miles in Trail
MMO	Mach Maximum Operating
MOA	Military Operations Area
MRC	Maximum Range Cruise
MSA	Minimum Sector Altitude
MSL	Mean Sea Level
MT	Montana, USA
NAS	National Airspace System
NASA	National Aeronautics and Space Administration
NAT	North Atlantic Tracks
ND	Navigation Display
NEAN	North European ADS-B Network
NextGen	Next Generation Air Transportation System
NG	Next Generation
NOTAM	Notice to Airmen
NUP2+	NEAN Update Program
NV	Nevada, USA

OAT	Outside Air Temperature
OFP	Operational Flight Plan
OIS	Onboard Information System
ONS	Onboard Network System
OPD	Optimum Profile Descent
PACeR	Precision Aircraft Control enhancing Route
PANS	Procedures for Air Navigation Services
PBN	Performance Based Navigation
PED	Personal Electronic Device
PFD	Primary Flight Display
PHARE	Programme for Harmonised ATM Research in EUROCONTROL
PIC	Pilot in Command
POD	Point of Deceleration
RBT	Reference Business Trajectory
RF	Radius to Fix
RNAV	Area Navigation
RNP	Required Navigation Performance
RPK	Revenue Passenger Kilometers
RTA	Required Time of Arrival
RTCA	Radio Technical Commission for Aeronautics
Rwy	Runway
SA	Situation Awareness
SAGAT	Situation Awareness Global Awareness Technique
SAM	Slot Allocation Message
SART	Situation Awareness Rating Technique
SATCOM	Satellite Communications
SBT	Shared Business Trajectory
SD	Standard Deviation
SES	Single European Sky
SESAR	Single European Sky Air Traffic Management Research
SFO	Senior First Officer
SID	Standard Instrument Departure
SoS	System of Systems
SPAM	Situation-Present Assessment Method
SSD	Solid-State-Drive
SSL	Secure Sockets Layer
STA	Scheduled Time of Arrival
STAR	Standard Terminal Arrival Route
STATFOR	Statistics and Forecast Service
STC	Supplemental Type Certificate
STW	Slot Tolerance Window

SUS	System Usability Scale
SWIM	System-Wide Information Management
TAS	True Airspeed
TBM	Time-Based Metering
TBO	Trajectory-Based Operations
TCA	Terminal Control Area
TCP	Trajectory Change Point
TGL	Temporary Guidance Leaflet
TLX	Task Load Index
TMS	Trajectory Management System
TOD	Top of Descent
TSO	Technical Standard Order
TUD	Technische Universität Darmstadt
TW	Target Window
TWR	Tower
USA	United States of America
VDL	VHF Digital Link
VDR	VHF Digital Radio
VHF	Very High Frequency
VMC	Visual Meteorological Conditions
VMO	Velocity Maximum Operating
VNAV	Vertical Navigation
VPN	Virtual Private Network
WGS-84	World Geodetic System - 1984
WiFi	Wireless local area network based on IEEE 802.11 standards
WSG	Worldwide Slot Guidelines
Wx	Weather
XML	Extensible Markup Language
XTE	Cross Track Error

1 Introduction

As an introduction to the realization and evaluation of an aircraft onboard retrofit Trajectory Management System (TMS) the motivation to conceptualize such system, the goals and the taken approach as well as the structure of the following thesis are described in this Chapter.

1.1 Motivation

Globalization is the driving factor of a worldwide increasing demand for air travel[1] [Wal13]. This demand is forecasted by AIRBUS and BOEING to result in worldwide air traffic growth rates of on average 4.7-5.0%[2] annually over the next 15-20 years [Air13a, Boe13]. The average aircraft size is not expected to increase over the next years and the load factor is limited in its growth [Cor10]. Therefore, this growth translates into a growth of demand in air traffic movements. The current Air Traffic Management (ATM) system is not capable to provide the additionally needed capacity to facilitate the expected increase in traffic as it is operating at the capacity limit already today at high traffic density airports [SES06a].

The INTERNATIONAL CIVIL AVIATION ORGANIZATION (ICAO) is proposing a set of operational improvements to meet these demand challenges in the *global air navigation plan* [Int13b]. There, Trajectory-Based Operations (TBO)[3] are described as one means to increase the airspace capacity. Beyond the capacity optimization the regional implementations of the ICAO *global air navigation plan* [Int13b], the Single European Sky Air Traffic Management Research (SESAR) in Europe [SES07] and the Next Generation Air Transportation System (NextGen) in the United States [Joi10] list a number of Key Performance Areas (KPAs) for optimization. The SESAR program aims to improve the ATM system in eleven KPAs. The four which are linked directly to performance targets from the European Commission are[4] [SES06b]:

- **Capacity:** Enable 3 times more air traffic.

[1] In detail WALDINGER names: mobility as a basic need, the growing world population, increasing urbanization, increasing international division of labor and the increasing prosperity as factors for a growth in air traffic [Wal13].

[2] Measured by Revenue Passenger Kilometers (RPK).

[3] A trajectory is the description of the aircraft movement in position and altitude over time. Compare to Section 2.2

[4] The remaining seven KPAs are: Access & Equity, Efficiency, Flexibility, Interoperability, Participation, Predictability, and Security [SES06b].

- **Safety:** Improve safety by a factor of 10.

- **Environmental Sustainability:** Reduce the environmental impact of each flight by 10%.

- **Cost Effectiveness:** Cut the ATM costs by 50%.

KLINGAUF describes the human, operations, and systems as the three fields that influence the performance in the KPAs as is illustrated in Figure 1.1 [KM13]. The human acts as decision maker in the ATM system whose performance in the various positions[5] has a direct influence on the system performance [HKC+97]. The operational procedures determine how much flow of air traffic is permitted per sector [SPB+11]. A change of procedures to include TBO will require new systems capable to perform these operations.

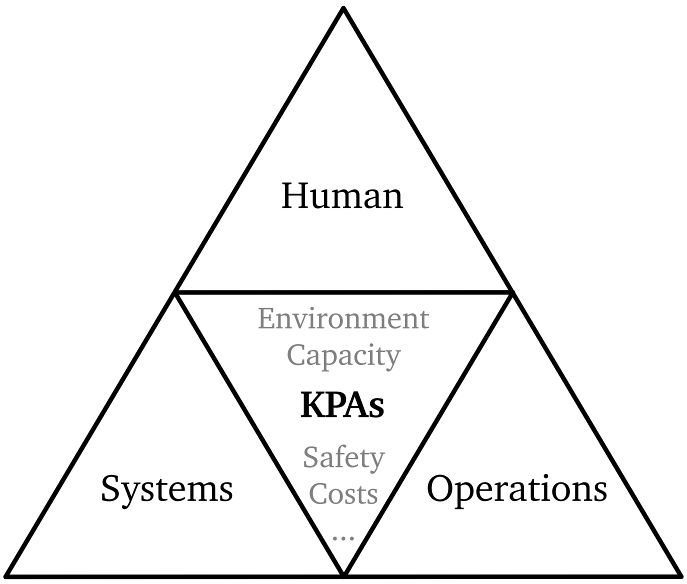


Figure 1.1.: Factors influencing the Key Performance Areas after KLINGAUF [KM13]

Previous works have identified that a high equipage rate is essential to improve performance in the specified KPAs with the utilization of TBO [DPLM13, SPB+11, KPS09]. Three options exist to integrate a TMS into an aircraft:

- A complete redesign of the Flight Deck to enable a native integration of the trajectory management.
- A retrofit integration into the aircraft avionics.
- A retrofit integration into additional hardware onboard.

[5] For example as pilot, Air Traffic Control Officer (ATCO) or ground handling agent.

1.2 Goals

This thesis discusses the challenge of an increase in demand of air traffic and its facilitation through the use of TBO. It aims to reach a high rate of participants. Near to mid-term developments are considered, to enable a cost-efficient retrofit equipage of aircraft with TMSs. This cost-oriented approach could potentially increase the equipage ratio thereby increasing the effect of TBO on the KPAs [KPS09]. Therefore, the third option, to integrate the TMS into additional hardware onboard, was determined to be the most suitable option for a retrofit integration of a TMS. The research question to be answered within this thesis is whether the functionality of a TMS can be integrated into an application running on an Electronic Flight Bag (EFB), as retrofit onboard hardware[6], to support the pilot in the execution of the flight within a TBO environment.

The goal of this thesis is to conceptualize and realize a retrofit onboard TMS that can easily be integrated into existing aircraft, and to evaluate the capability to perform TBO with the developed system. The objective of the conceptualized TMS is to fulfill the following tasks necessary for an onboard trajectory management:

- **Negotiation:** Enable the communication of trajectories with the Airline Operations Center (AOC) and Air Navigation Service Provider (ANSP) and a briefing by the pilot.

- **Monitoring:** Enable the eased monitoring of the aircraft trajectory performance relative to the contracted trajectory.

- **Guidance:** Enable an aircraft guidance along the contracted trajectory, either through a Human-in-the-Loop (HITL) or automatic integration.

The system is realized and evaluated to answer the question regarding whether the conceptualized functions of the TMS aid the pilot's Situation Awareness (SA) and help in decision making. In addition, different guidance integrations are evaluated to determine if they can be integrated into the workflow of the pilot, interface with the aircraft systems when needed, and produce a satisfactory guidance performance.

1.3 Approach

An aircraft-centric approach is chosen to evaluate the interaction of the pilot with the system and the resulting performance. This approach allows the assessment on how additional tasks of the trajectory management can be integrated into the workflow of the pilot. In contrast to a holistic fast time simulation, this approach does not quantify the direct benefit of the introduction of the conceptualized TMS on the KPAs. It does, however allow the collection of performance data in evaluations that can model pilot behavior with the

[6] See Section 2.5 for details of the concept of an EFB.

realized TMS in a fast-time simulation. Therefore pilot performance is considered early in the design phase. Redefining workflows of the ATM system consider the pilot performance with the system. This approach avoids to force the pilot workflow into an already finalized system, not supporting the cognitive ergonomics of the pilot.

The onboard retrofit TMS is designed as decision support tool for the pilot, to determine the best suitable trajectory for the mission of the flight and to execute it. The system is designed by using a human centered design approach. This approach aims on supporting the SA of the pilot, to enable better decisions and a better and more efficient performance of the flight.

In a first step, current operational procedures and their expected changes towards TBO are analyzed along with current aircraft avionics. This step allows to determine the operations and functions a potential TMS needs to support. It also allows to determine possible integrations with existing aircraft systems. The pilot shall remain an integral part of the mission management. Therefore, the TMS is designed as decision support tool for the pilot. Cognitive ergonomics are discussed with a focus on a human-centered design of the TMS to support the pilot's SA.

From this foundation, a TMS is conceptualized that supports the functions of trajectory negotiation, monitoring, and guidance. It also integrates with different systems onboard the aircraft and with the stakeholders of ANSP and AOC on the ground.

The TMS is evaluated in simulator and flight trials to determine the performance of the guidance and the performance of the pilot using the system. The goal is to identify if the realized system can perform the tasks of trajectory negotiation, monitoring and guidance in the different integrations. In addition, the usability is evaluated to determine potential for optimization of the workflow and the Human Machine Interface (HMI). The temporal performance of the guidance is evaluated in the trials to quantify the performance of HITL 4D guidance[7] and demonstrate its operational integration.

1.4 Structure

The thesis is structured into eight Chapters and four Appendices as illustrated in Figure 1.2.

- **Chapter 2** provides an overview of the current state of the art in ATM procedures and technologies. The expected changes to the ATM system and possible descriptions of an aircraft's trajectory are discussed. To communicate the trajectory between stakeholders, data link communication systems are needed. These systems are presented along with the onboard systems of Flight Management Systems (FMSs) and EFBs to evaluate an integration of a TMS in current flight decks.

[7] 4D refers to the four dimensions controlled by the guidance: latitude, longitude, altitude, and time at the defined position.

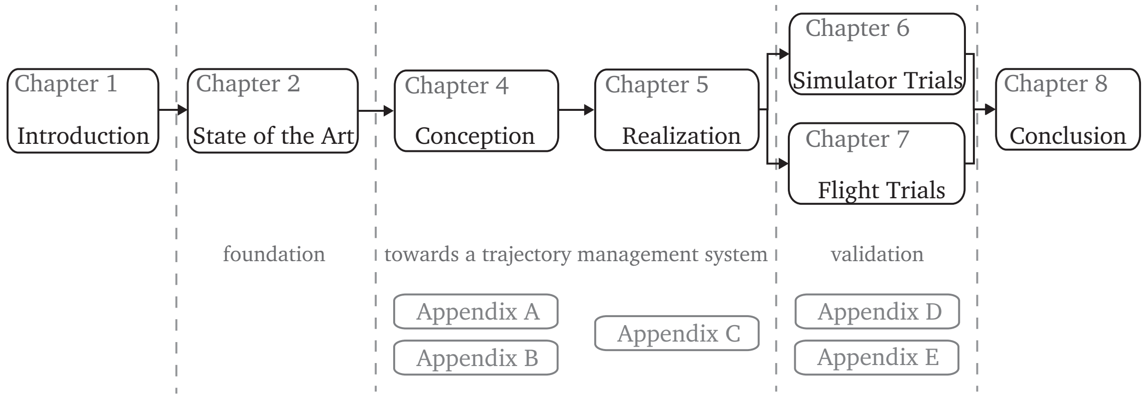


Figure 1.2.: Structure of the thesis

- **Chapter 3** presents the ideas conceptualized for the onboard retrofit TMS. The operational environment in which the TMS is integrated is defined. From this design considerations to be applied in the conceptualization are discussed and the three TMS functions of trajectory negotiation, monitoring and guidance are differentiated.
- **Chapter 4** considers the results of Chapter 3 and integrates them into a research charting EFB application as working prototype of the TMS.
- **Chapter 5** examines the hypotheses set for the developed TMS during simulator trials in the TECHNISCHE UNIVERSITÄT DARMSTADT (TUD) research flight simulator. The concept of the trials, their execution and analysis is discussed.
- **Chapter 6** describes the results of two flight trial campaigns performed within the scope of this thesis with the realized TMS.
- **Chapter 7** concludes the thesis and provides an outlook for future developments.

The work presented in Chapters 3 to 6 is supported by data provided in Appendices A through E which aims to aid in the understanding of the work presented in the corresponding Chapter.

- **Appendix A** provides further background on the cognitive ergonomics.
- **Appendix B** details aircraft performance calculations which are applied applied for the monitoring function of the conceptualized TMS.
- **Appendix C** presents additional data on the realized TMS and the development process as well as the details of the trajectory exchange model.
- **Appendix D** lists the evaluation data of the trials in the TUD research flight simulator. Details on the setup and the gathered data are presented.
- **Appendix E** provides data on the architecture and performance of the two flight trial campaigns, as well as for the preceding simulator trials.

2 State of the art of air traffic management and aircraft systems

The Air Traffic Management (ATM) system is a complex System of Systems (SoS) [Cro04]. To define, design, and develop a system within the ATM environment, an understanding of those systems and their interfacing subsystems is needed. Therefore, the expected global changes in the ATM systems are detailed using Trajectory-Based Operations (TBO) to meet the demand challenge [Int05]. Trajectory definitions to be applied in this thesis are compared. Aircraft communication systems are discussed and can be used to share the trajectory between stakeholders, followed by an overview of current avionics hardware and software in Flight Management Systems (FMSs) and Electronic Flight Bags (EFBs), to support the trajectory management.

2.1 Change in the ATM system

Knowledge of how an intended flight is managed before and during the flight execution is required to meet the demand challenge of designing an effective ATM. This Section provides an overview of today's capacity management and its shortcomings in handling an increase in capacity are described. This Section also discusses how the ATM system will be remodeled in the future and how this will affect the planning and execution of a flight.

2.1.1 The current ATM environment

Today's ATM system limitations are driven by insufficient capacity coordination shortcomings [Fro98]. The largest capacity discrepancy occurs at the airport and in congested airspaces [BDO01]. Therefore, tools have been implemented by the Air Navigation Service Providers (ANSPs) and national regulating bodies for the enhancement of the strategic airport slot allocation and enroute Air Traffic Flow Management (ATFM).

Airport slots

Airport capacity is one of the "bottle necks" of the current ATM system [DH05]. Outside the United States[1], airport slots are assigned at more congested airports. The International Air Transport Association (IATA) has developed the Worldwide Slot Guidelines

[1] In the United States, airport slots are not commonly used. Airlines can plan flights independently and the cost of delay limits the demand at airports [EF12].

(WSG) [Int13a], a set of rules for the allocation of airport slots. Since not all airports are subject to airport slot allocation, the WSG has defined three airport levels:

- **Level 1 Airports** are non-congested and do not require coordination of available airport capacity.
- **Level 2 Airports** have, at times, a demand higher than the available capacity, which is resolved by voluntary coordination between the operators.
- **Level 3 Airports** generally lack capacity to meet the demand. An appointed coordinator is assigning departure and landing slots to operators on the airport to manage the available capacity.

The IATA defines an airport slot as [Int13a]:

> "*...a permission given by a coordinator for a planned operation to use the full range of airport infrastructure necessary to arrive or depart at a Level 3 airport on a specific date and time.*"

The assignment of the slots on Level 3 airports is performed by an independent entity, the airport coordinator, conforming to the thirteen IATA WSG principles of slot allocation. These principles provide a transparent set of rules for the slot assignment which is performed twice a year for summer and winter seasons, and coordinated by the IATA slot conference [Int13a].

In Germany, all international airports[2] are either Level 2[3] or Level 3[4] airports [Wal13]. Therefore, most commercial flights in Germany [Sta13b] require the previous allocation of a departure and landing slot even though the IATA states that [Int13a]:

> "*Coordination should be seen as an interim solution to manage congested infrastructure until the longer-term solution of expanding airport capacity is implemented.*"

Air traffic flow management

Although airport slot assignment provides a strategic means to coordinating the available airport capacity, the ATFM provides more tactical-driven, enroute capacity coordination [Wal13]. The International Civil Aviation Organization (ICAO) *Procedures for Air Navigation Services (PANS)-ATM* [Int07a] defines ATFM as:

> "*...a service established with the objective of contributing to a safe, orderly and expeditious flow of air traffic by ensuring that Air Traffic Control (ATC) capacity*

[2] Classified using the differentiation of §27d *Luftverkehrsgesetz*[luf] if a federal interest is present.
[3] Bremen, Dresden, Erfurt, Hamburg, Hannover, Cologne/Bonn, Leipzig/Halle, Münster/Osnabrück, Nürnberg, Saarbrücken [Wal13].
[4] Berlin Airports (Schönefeld and Tegel), Düsseldorf, Frankfurt am Main, Munic, Stuttgart [Wal13].

> *is utilized to the maximum extent possible, and that the traffic volume is compatible with the capacities declared by the appropriate Air Traffic Service (ATS) authority.*"

The ICAO differentiates three phases of flow management [Int07a]:

- **Strategic Flow Management** is the long-term capacity planning, more than one week in advance, based on forecasts and extra traffic by special events.
- **Pre-Tactical Flow Management** updates the initial planning of the strategic flow management once updated data, such as filed flight plans[5], are available, between one week and up to one day before operation.
- **Tactical Flow Management** takes place on the day of operation and uses slot allocation and re-routings to manage traffic.

From these general definitions, the implementation into operations differs from the region where it is applied. The following sections give an overview of the ATFM implementations in Europe and the United States.

Europe

In Europe, the European Organisation for the Safety of Air Navigation (EUROCONTROL) Central Flow Management Unit (CFMU) serves as the centralized ATFM unit. This service was taken over from the national ATFM units in 1996 [Fou05]. The increasing delays in the 1980s prove that a centralized approach to ATFM can best allocate the resource airspace [Fou05]. The objective is to accommodate more air traffic per surface, with a higher involvement of stakeholders and national interests, in a fractioned airspace system, as illustrated in Figure 2.1, by the Flight Information Region (FIR) boundaries. This adds more complexity to the flow management, compared to the United States, where the air space is operated by one entity [EF12].

The CFMU supports pre-tactical and tactical flow management. Flight plans are collected through the Integrated Initial Flight Plan Processing System (IFPS) that distributes the flight plan to all involved Air Traffic Services Units (ATSUs). Based on the flight plan information, the Enhanced Tactical Flow Management System (ETFMS) calculates a 4D Trajectory for the flight which is used to estimate the demand at the ATSUs and airports. If the demand exceeds the available capacity, the ETFMS assigns departure slots on a tactical basis on the day of operations. A Slot Allocation Message (SAM) is sent to the aircraft operators and ATC which defines a Calculated Take-off Time (CTOT) with allowed deviations[6]. To support strategic flow management in the future, the CFMU will have to evolve

[5] Tanner [Tan08] provides a comprehensive overview of the information included in an ICAO flight plan, according to the *ICAO PANS-ATM* [Int07a].

[6] Standard values for the Slot Tolerance Window (STW) are five minutes before the CTOT and ten minutes after. For non-controlled flights the standard values for the Departure Tolerance Window (DTW) are fifteen minutes before and after the CTOT. Deviations from these standard values are possible [Eur13].

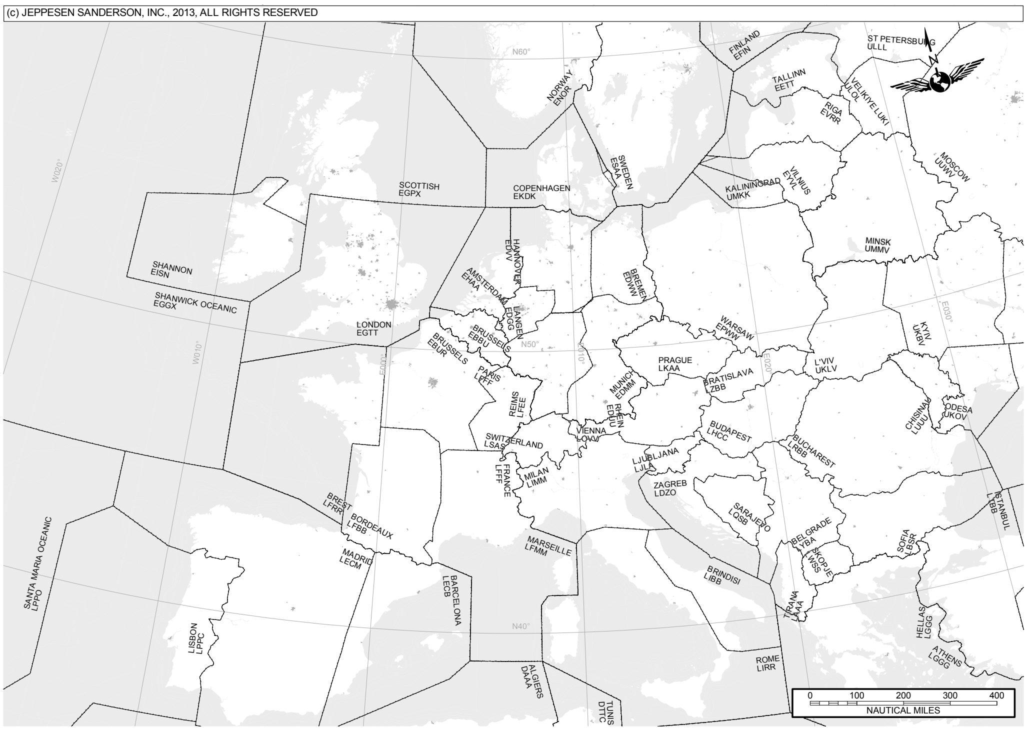


Figure 2.1.: Fragmented central european airspace created with JeppView [Jep13]

from ATFM to Air Traffic Flow and Capacity Management (ATFCM). This can be achieved through an increase of Collaborative Decision Making (CDM) with involved stakeholder, taking the EUROCONTROL Statistics and Forecast Service (STATFOR) demand forecasts for long-term capacity planning into account [Fou05, Eur05a].

United States

In the United States, ATFM is performed through a CDM process with participation from all stakeholders. The Air Traffic Control System Command Center (ATCSCC) of the Federal Aviation Administration (FAA) facilitates the CDM process and coordinates the capacity. Adverse Weather (Wx) is less frequent than in Central Europe; however convective Wx is the most disruptive Wx factor in the United States [Int12a]. As convective Wx occurs only locally, and the traffic is managed on a national level, disruptions can be approached tactically. To coordinate disruptions, CDM teleconferences are held every two hours to gage the current capacity [FAA06]. Ground restrictions from Estimated Departure Clearance Times (EDCT) assigned by the ATCSCC are less common than the CTOT restrictions in Europe, and are used only in cases of severe capacity restrictions. For most operations, the tactical flow management is performed enroute by Time-Based Metering (TBM), or by Miles in Trail (MIT) with the objective to optimize arrival runway capacity, as enroute capacity limitations are less frequent than airport capacity restrictions. The centralized airspace structure in the United States allows the coordination of arrival traffic already outside of the Terminal Control Area (TCA) [EF12].

Flight execution

Clearances serve as the interface between flight phases and ATSUs or ground service providers. Flights are executed on a tactical clearance basis. Once a startup clearance is assigned, the flights are no longer subject to ATFM, but treated on a "first-come/first-served" basis [Int07a].

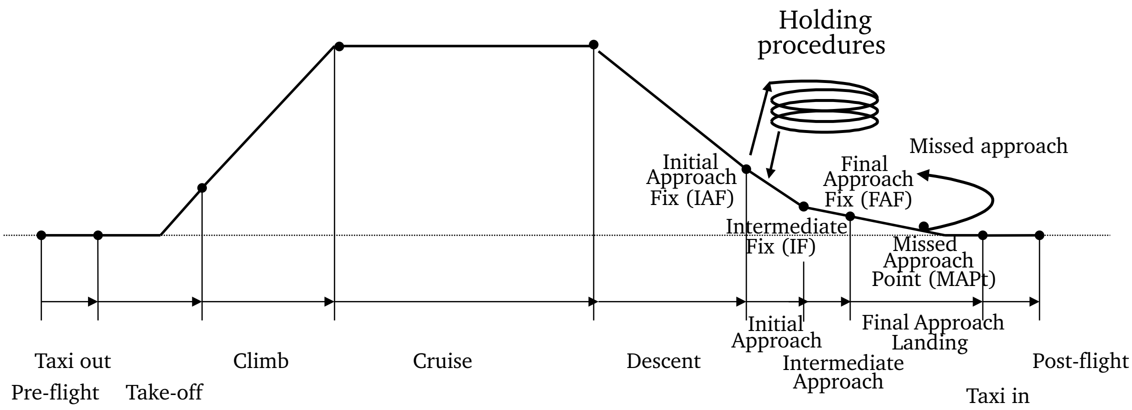


Figure 2.2.: Phases of flight after WALDINGER [Wal13]

A flight can be divided into phases from the departure gate to the gate at the destination airport, as illustrated in Figure 2.2. After startup, the aircraft is cleared for a taxi route on the airport to the departure runway. The next clearance includes the permission for take-off and the initial routing on a Standard Instrument Departure (SID). After departure, additional clearances permit the aircraft to attain cruising altitude. While enroute, the aircraft is handed over from one ATSU to another and cleared for the flight within each sector. Since each sector operates independently, the optimization of the flight is difficult and involves manual coordination of the controllers from different ATSU via phone to allow a more direct routing or optimized Flight Level (FL). Once arriving in the vicinity of the destination airport, the aircraft becomes subject to TCA flow control. Descent clearances are given for the descent depending on the traffic situation, either via radar vectoring or on Standard Terminal Arrival Routes (STARs). If the airport runway capacity does not permit an immediate landing, either holding patterns are assigned to the aircraft at the Initial Approach Fix (IAF) or a longer trombone approach to sequence and delay traffic is used. Depending on the Wx situation and aircraft capability, the flight is cleared on a published approach procedure. On the ground, the aircraft is cleared to taxi to the destination gate via an assigned taxi route [Wal13, Int07a].

2.1.2 The future ATM environment

The ICAO devised a plan that proposes how to approach the challenges of today's ATS. The *Global Air Traffic Management Operational Concept* [Int05] describes the ICAO vision of the future ATM system, with guidelines for implementation in the *Global Air Navigation Plan* [Int13b]. Today's national ATM systems operate independently. In the future these systems shall be integrated, harmonized among national interests, and ensure a global interoperability.

From the global ICAO plan, regional implementations have evolved to foster the development of new ATM systems. For this thesis, the United States Next Generation Air Transportation System (NextGen) and the European Single European Sky Air Traffic Management Research (SESAR) projects serve as examples of how the top-level ICAO vision is transferred into operational practice.

Concept

Instead of handling the various challenges of increasing air traffic with several different tools and available information, as in the past, the trajectory-based ATM allows an integrated approach to all operational restrictions. In Europe, the term "Business Trajectory" describes the airspace users' preferences. In the United States, the process of the trajectory lifecycle is named Collaborative - Air Traffic Management (C-ATM). The trajectory description evolves over time, as illustrated in Figure 2.3, but is continuously used from strategic planning to flight execution by all stakeholders. The airspace user is the owner of the trajectory and the ATM system tries to enable a flight as close to the airspace users' intentions as possible. The trajectory lifecycle process starts with the intention of the airspace user to perform a flight. The Business Development Trajectory (BDT) describes the airspace user intentions for the flight service. Once the BDT is stabilized it is shared among all involved stakeholders to identify possible constraints and is referred to as the "Shared Business Trajectory (SBT)" which is iteratively updated to optimize the overall network performance. Once the trajectory is agreed among all stakeholders on the day of execution it becomes the Reference Business Trajectory (RBT), which is still updated to reflect changed constraints or deviations to the intended trajectory. Operational experience from the execution of the flight is fed back to the BDT and SBT to improve future operations [SES07, Joi10].

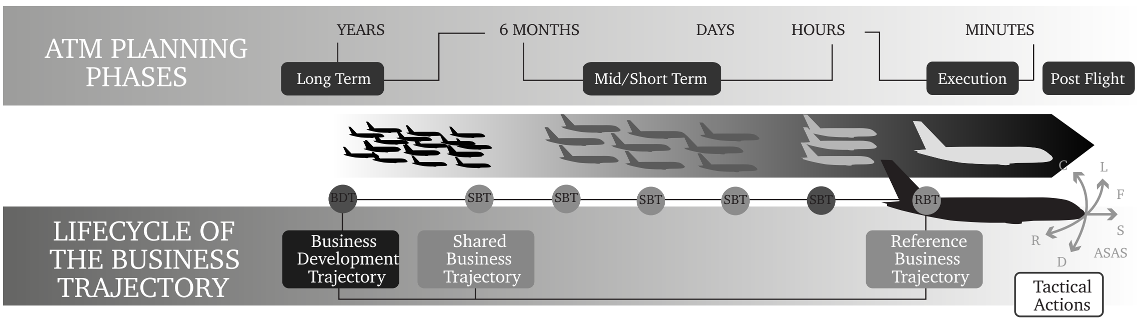


Figure 2.3.: Business Trajectory Lifecycle [SES07]

The sharing of a trajectory for a CDM process among all involved stakeholders demands the sharing of other relevant operational information to ensure the same information basis for decision making. The ICAO concept describes System-Wide Information Management (SWIM) as a framework for the distribution of relevant information that was adapted by the SESAR and NextGen concepts [Int05, SES07, Joi10].

Realization

With implementation of both European SESAR and NextGen in the United States, the concept of a trajectory-based ATM is becoming a reality.

In Europe, the *SESAR ATM Master Plan* [SES12] defines the implementation of technologies to enable improvements in the SESAR Key Performance Areas (KPAs). The plan is structured into three deployment steps to evolutionarily change the ATM system from current operations to performance based operations. The first step defines a change to time-based operations which includes the usage of Initial 4D (I-4D), initial SWIM capabilities, and will be based on increased trajectory sharing. In a second step, the system is transformed to trajectory-based operations including the use of full 4D trajectories with multiple Required Time of Arrivals (RTAs), and a full SWIM integration, as evolution of the first step. The third step to performance-based operations shall take the performance capabilities of every individual flight into account, but technological enablers are not yet defined.

Besides the technological efforts to change operations, the Single European Sky (SES) II legislature plans to decrease the fractioning of the European airspace system. Through the harmonization of the airspace and its structuring in Functional Airspace Blocks (FABs), as shown in Figure 2.4, coordination and integration should be eased, thus allowing an easier technical implementation of the enablers that rely on information sharing [Eur08b].

The FAA describes their realization efforts in the *NextGen Implementation Plan* [Fed13a] and *Capital Investment Plan* [Fed12c]. The focus is on the development of procedures and technologies to be operational until 2017. With an existing centralized ATM system in the United States, the focus is on technological enablers to increase the airport capacity. The current implementation efforts are focusing on Performance Based Navigation (PBN)[7] and distribution of ground and airborne Automatic Dependent Surveillance - Broadcast (ADS-B) systems. Further development will include applications which utilize ADS-B in, and data link to increase the capacity of the National Airspace System (NAS)[8]. interoperability with the European SESAR efforts is ensured through a U.S.-E.U. mem-

7 PBN includes Required Navigation Performance (RNP) and Area Navigation (RNAV)-based terminal procedures and enroute navigation [Int08].

8 It should be noted that only a small subset of functionalities and procedures under development as envisioned are described. For detailed information refer to the *SESAR Master Plan* [SES12] and *NextGen Implementation Plan* [Fed13a].

Figure 2.4.: European functional airspace blocks [Eur08b]

orandum and compatible with the ICAO Aviation System Block Upgrades initiative to coordinate global ATM modernization efforts [Int11b].

In order to apply the defined concepts, a detailed understanding of a trajectory description and its capabilities is needed.

2.2 Definition of a trajectory

A trajectory is the description of an objects movement through space over time. For an aircraft, the position is described in a geodetic coordinates system as latitude ϕ, longitude λ and height h[9]. The change of the position over time t describes the aircraft's 4D trajectory.

$$f(t) = \begin{pmatrix} \phi \\ \lambda \\ h \end{pmatrix}, \forall \begin{cases} \phi & \in & [-90°,90°] \\ \lambda & \in & [-180°,180°] \\ h & \in & \mathbb{R}^{\geq -414}\ \mathrm{m} \\ t & \in & \mathbb{R}_0^+ \end{cases} \tag{2.1}$$

[9] According to the ICAO [Int04], the World Geodetic System - 1984 (WGS-84) datum defines the standard for horizontal navigation and the elevation above Mean Sea Level (MSL) datum (or up to 414 m below MSL for the lowest point on earth) for vertical navigation with the Earth Gravitational Model - 1996 (EGM-96) as global gravity model.

This mathematical description can be applied in a discrete or continuous manner allowing different forms of deviations in each dimension. In the following, three different utilizations of 4D trajectories are described and examples of each description are given. It should be noted that the selected three trajectory descriptions are only a small subset of possible trajectory descriptions and combinations of these definitions are possible. Other approaches[10] are conceivable, but fall outside of the scope of this thesis.

2.2.1 Initial 4D

The concept for an I-4D trajectory description derives from the *NEAN Update Program (NUP2+)* project [Fri07], which developed and demonstrated Advanced - Continuous Descent Approach (A-CDA) operations at Stockholm Arlanda Airport based on 4D Trajectories [WKBR07, KWB08]. Later flight trials followed within the *CTA/ATC System Integration Studies (CASSIS)* project [KAM09, Pro10, Mem10, Mem09, Pro09]. It was refined as the Concept of Operations (ConOps) of the 4D Trajectory Data Link (4DTRAD) [Eur08a] and demonstrated within SESAR on an Airbus test flight in 2012 [Eur12a].

I-4D defines a trajectory exchange between a ground service and an aircraft to negotiate a 3D trajectory and coordinate a RTA for one waypoint in the approach phase. The system is based on trajectory sharing of the aircraft through an Automatic Dependent Surveillance - Contract (ADS-C) service [KTE+10]. The trajectory negotiation can be divided into six phases as shown in Figure 2.5.

First, the aircraft downlinks its 4D projected profile via ADS-C to the ground service. This intent includes a lateral route, altitudes, and minimum and maximum achievable Estimate Times of Arrival (ETAs) over waypoints of the route. From the initial intent, a lateral 2D route is agreed between the pilot and the controller. This route can (but does not have to) be identical to the initial intent of the aircraft. A vertical profile is calculated using the agreed 2D route, and approved by the ground service. The aircraft FMS calculates updated minimum and maximum ETAs for all waypoints of the trajectory and shares this trajectory information via ADS-C. To coordinate with other arriving traffic, the ground service imposes an RTA in the TCA of the aircraft's destination airport. The aircraft continues to share its intended trajectory and minimum/maximum ETAs via ADS-C during this execution [Eur08a].

Temporal adherence

The temporal adherence along the trajectory is restricted through a departure slot, and the assigned RTA in the terminal area of the destination airport. This results in a large enroute temporal flexibility along the trajectory. Figure 2.6 illustrates the resulting temporal flexibility, showing the temporal deviation Δt to a calculated reference trajectory

[10] For examples Leones definition of the Aircraft Intent Description Language (AIDL) [Leo08, LLVG+07] to describe the aircraft's trajectory as a set of expected configuration changes of the aircraft.

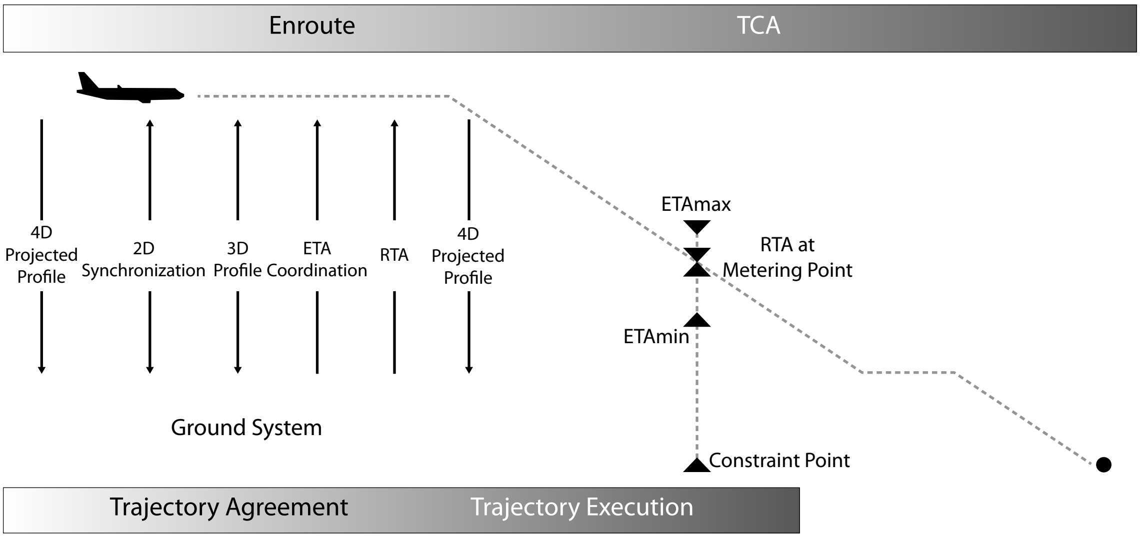


Figure 2.5.: I-4D trajectory coordination [Eur12a]

over the lateral distance s of the trajectory from departure to destination. The larger the distance from a constraint (in this case the departure slot or the assigned RTA the larger the possible temporal deviation Δt from the reference trajectory. The definition of an RTA without allowed deviations does not permit to switch the ATM paradigm from "first-come/first-served" to "timely-come/timely-served", as a boundary to identify non-timely flights would have to be defined. The purpose of the I-4D integration is to assist the arrival controller in managing arrival streams and optimize the arrival capacity of the airport. Jackson discusses a concept how the system can be used to enable Continuous Descent Approach (CDA) operations in a mixed-equipage environment [Jac09].

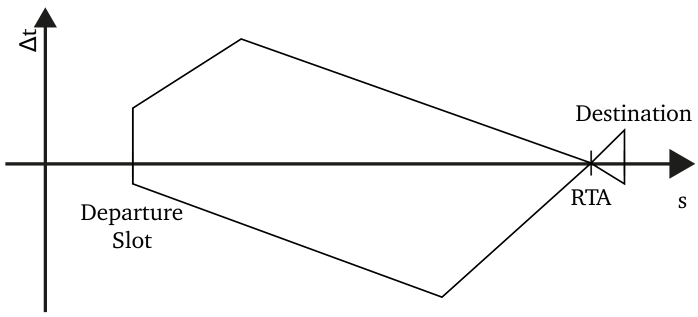


Figure 2.6.: Time flexibility of an I-4D flight over the trajectory

Applicability

The concept of assigning an RTA at one waypoint in the arrival phase of the trajectory can help to coordinate arrival streams of aircraft [HH12]. Once a major operator at an airport adopts the system, it can realize full benefits of a locally based system. One disadvantage in adopting a Future Air Navigation System (FANS)/4DTRAD equipment-based system is the high starting investment costs needed to put the system in place. Operational improvements are necessary to recover these costs [JGMS13]. However, for major operators at airports supporting I-4D, the increase in predictability of landing times can help to coordinate ground processes and reduce fuel burn[11], providing cost savings for the aircraft operator [Eur08a].

2.2.2 Full 4D

The full 4D trajectory concept originated in the EUROCONTROL *Paradigm SHIFT* Project [Eur05b]. One key element of the concept is the Contract of Objectives (CoO). The CoO defines constraints and temporal Target Windows (TWs) on waypoints along the trajectory that must be met by the aircraft to ensure an efficient flight. The concept was refined and evaluated with Human-in-the-Loop (HITL) controller experiments in the Contract-based Air Transportation System (CATS) Project [GGCR08, Eur10, GGR09, GGR10a, GGR10b]. Figure. 2.7 illustrates how multiple TWs along the trajectory limit the temporal envelope of the aircraft, while allowing optimization within the constraints.

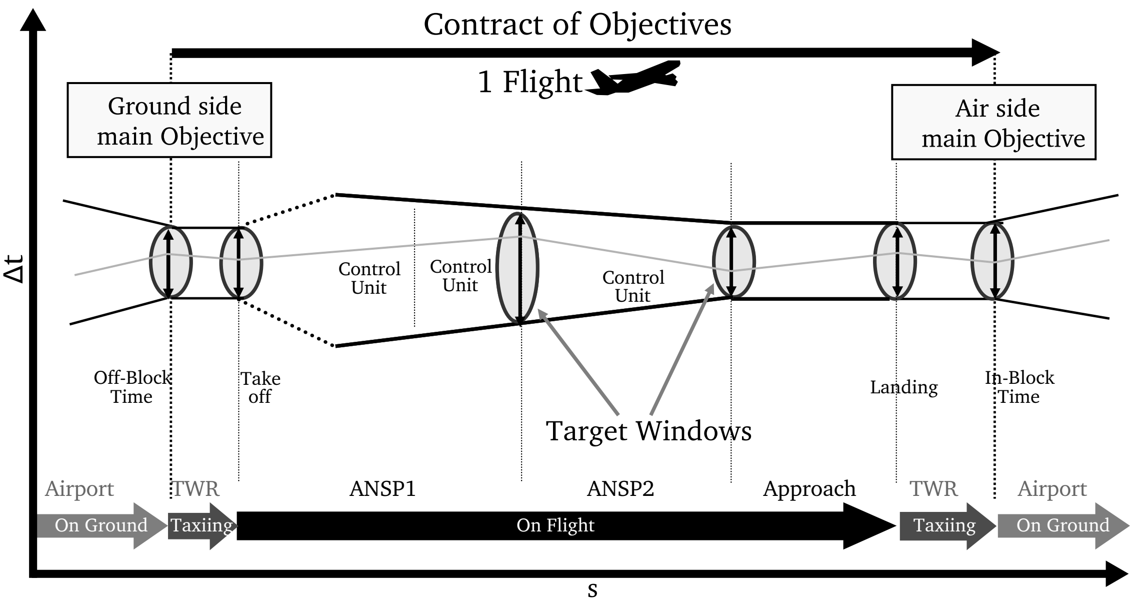


Figure 2.7.: The "contract of objectives" and its envelope after GUIBERT ET AL. [GGR10b]

Temporal adherence

The concept allows four different types of temporal constraints. A "**between**" constraint corresponds to the idea that TWs at waypoints needs to be crossed *between* two defined

[11] Operators can expect reduced fuel burn because of decelerations enroute when an RTA does not allow earlier-than-planned arrivals [Eur08a].

times. To allow flexibility in the constraint definition, constraints can also have the format "**at or later**" or "**at or earlier**" to define *early* or *late* limits for when a waypoint needs to be passed. In order to ensure interoperability with the I-4D concept, "**at**" constraints can be imposed to fly over at the *exact* time specified. This concept was also applied by the FMS developed by Korn and Kuenz of the Deutsches Zentrum für Luft- und Raumfahrt e.V. (DLR) [KK06]. Jackson et al. propose a control method and negotiation process to follow multiple RTAs constraints that is in line with the CATS concept [JO07].

The resulting temporal flexibility along the trajectory is displayed in Figure 2.8 considering exemplary "**between**" and one "**at or earlier**" constraint as well as the departure slot. It can be seen how the temporal flexibility is influenced at different constraint points. The goal is to only constrain parts of the trajectory where constraints are needed, ensuring a flight maintains the most optimal trajectory possible. As multiple temporal constraints can influence one another[12], Ballin et al. [BWAP08] propose a method for relaxing RTAs to meet the most important constraints if not all constraints are feasible. This constraint relaxation assumes that some TW constraints maybe subject to some tolerance.

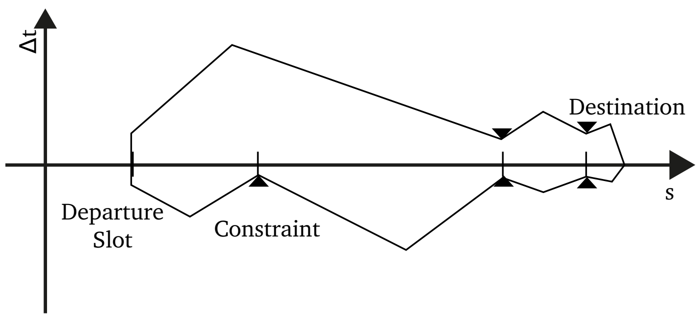


Figure 2.8.: Time flexibility of a full 4D flight

Applicability

Describing a trajectory by waypoint constraints enables a 4D trajectory that can be applied in all phases of flight. As Figure 2.7 shows, the TWs or constraints can be used to interface between different phases of flight. The trajectory is defined gate-to-gate for one flight (off-block to in-block for the aircraft). The TWs of the trajectory originate from different owners. The off-block and in-block TWs are defined by the ground processes, the take-off and landing TWs by the airport capacity, and enroute TWs by the sector capacity. Thus, the CoO allows a CDM across all ATM stakeholders [Eur10]. Using TWs or other described constraint types allows the ATM shift to "timely-come/timely-served".

The trajectory description requires only a list of waypoints and minimum and maximum limits for altitude and RTA at each waypoint. This information allows a strategic trajectory definition that can be used to allocate and deconflict sector or airport capacity for

[12] The achievable times at waypoints are limited by the aircraft envelope or economic considerations.

contracted TWs [Eur10]. However, the description cannot be used for a deconfliction of the flight path itself. Large deviations to the nominal 4D trajectory occur already close to the restricting TW and propagate along the trajectory. This deconfliction from traffic has to either be managed onboard by Airborne Separation Assurance System (ASAS) tools or through a continuous trajectory description.

2.2.3 Continuous trajectory

The concept of a continuous trajectory description allows the translation of the RNP concept[13] from a lateral to a temporal domain [Rad03]. Ballin et al. apply continuous 4D guidance in the National Aeronautics and Space Administration (NASA) 4D-FMS [BWAP08] to fulfill constraints on a trajectory description similar to the full 4D concept. The continuous trajectory guidance algorithm implemented into the NASA 4D-FMS maintains the pre-calculated reference trajectory within the given RNP deviations for the segment.

Figure 2.9 visualizes the desired location, with the allowed RNP deviation that translates from a time deviation into a lateral deviation, taking the planned ground speed into account. As the position of the aircraft can only be estimated within a given accuracy, the Actual Navigation Performance (ANP) defines the uncertainty of temporal navigation performance. The range error plus the ANP must be smaller than the temporal RNP limits 95% of the time.

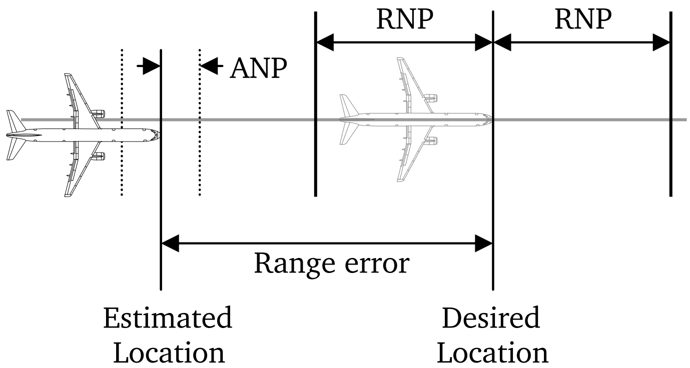


Figure 2.9.: Required and actual temporal navigation performance after Ballin et al. [BWAP08]

Similar applications of a continuous trajectory definition are used in the *Programme for Harmonised ATM Research in EUROCONTROL (PHARE)* [vGS99, CDEN95, EHQ96] and *4D Contract - Guidance and Control (4DCo-GC)* [JT12] projects where "tubes" or "safety bubbles" are negotiated between the ATM air and ground stakeholders. Gomez and Garrido-

[13] RNP refers to a navigation concept which requires the onboard monitoring and alerting of the cross track error to the defined RNP route or procedure. This functionality allows high precision lateral trajectories [Int08].

Lopez [LNF07, GLDL09] describe another continuous trajectory arrival guidance method. The application called *Continuous Descent Approach for Maximum Predictability (CDA-MP)* enables highly predictable CDA operations and can be used for merging and spacing applications in the TCA, as it allows adherence to a continuous 4D trajectory while minimizing throttle activity in the descent.

Temporal adherence

The continuous trajectory description differs from I-4D and full 4D, as the trajectory is not described as a set of discrete points but as a continuous function of time. The allowed temporal deviation is defined for each segment of the trajectory rather than for each waypoint. Ballin et al. propose temporal RNP values between 15 and 180 seconds, depending on the phase of flight [BWAP08]. The transition between two temporal RNP values can either be discontinuous, as shown in Figure 2.10, or continuous, between two temporal RNP values, as described by Ballin et al. [BWAP08]. As separation from other traffic can only be ensured with small temporal deviations in high traffic situations, reaction to disturbances has to be imminent rather than economical. The most economical flight is assumed to be least subject to ATC constraints.

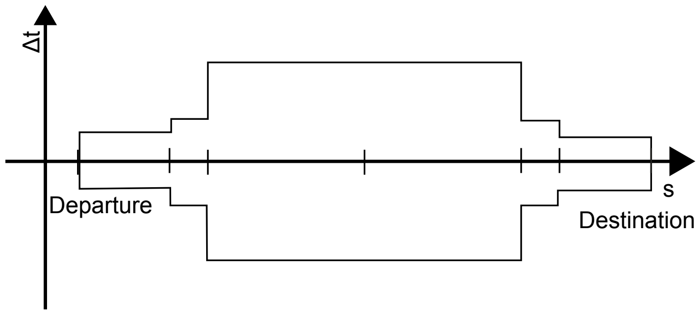


Figure 2.10.: Time flexibility of a continuous trajectory flight

Applicability

A continuous trajectory description allows separation, merging and spacing of aircraft on the same lateral trajectory. The protection space around the aircraft[14] must not be penetrated, with all trajectories free of conflict and adhering to the trajectories ensured through onboard monitoring and alerting (compare to the lateral concept of RNP [Rad03]). One application of a continuous trajectory description that is shared with a ground station is arrival operations in the TCA. Continuous trajectory descriptions cannot be briefed in detail by a human operator because of the vast amount of data used to describe the trajectory. Monitoring of the trajectory adherence onboard the aircraft and on

[14] The protection space can be described in multiple ways depending on the application. Barraci [Bar09] e.g., describes the protection space as cylindrical zone with elliptic base.

the ground[15] increases the integrity of the trajectory adherence. Jackson compared the presented three trajectory definitions, arguing that a continuous description exceeds the task of a trajectory[16] and should only be used when increased predictability is required [Jac10].

Another onboard application is the relative continuous trajectory, where the trajectory is not georeferenced, but uses another aircraft's position as reference [BWAP08]. This application is not focused on the strategic aspects of a 4D trajectory, but instead serves as ASAS. An ASAS application of relative aircraft spacing is available as a retrofit product SafeRoute from Aviation Communication & Surveillance Systems (ACSS) [ACS13, PB08], which uses ADS-B data, a guidance algorithm, calculated guidance on a Cockpit Display of Traffic Information (CDTI), and an additional display.

2.3 Aircraft communication systems

The description of an aircraft's 4D trajectory can only be used as a tool to optimize ATM processes when shared among the ANSP, Airline Operations Center (AOC), and the aircraft, as illustrated in Figure 2.11. Thus communication systems are required onboard the aircraft, to communicate with the ANSP and AOC. In the past, communication between the stakeholders was mostly voice-driven. In the future, the negotiation and communication of complex trajectories can only be facilitated over data link, and includes all three stakeholders of the ATM system.

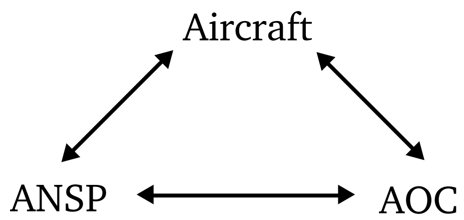


Figure 2.11.: Communication triangle between ATM stakeholders after Pufahl [Puf12]

2.3.1 Voice communication

Since its introduction in 1917, radio voice communication has become the de facto standard for in-flight aviation communication [TT13, TW07]. The communication uses standardized phraseology defined by ICAO in *Appendix 10*, *PANS-ATM* and the *Manual of Radiotelephony* [Int06, Int07a, Int07b] that ensures efficient communication and reduces the risk of corrupted information from bad transmissions.

15 With the assistance of automation tools such as the "slot marker" described by Kupfer et al. [KPC+11] or other "ghosting" symbology patented by NAV Canada [BBC+06].

16 Increased throttle activity needed to stay on the planned 4D trajectory results in high engine wear, low fuel economy, and low ride quality.

Each ATC sector operates on an independent Very High Frequency (VHF). All aircraft can hear the ATC instructions to any aircraft in the sector. This increases the Situation Awareness (SA) of pilots with a mental picture of the surrounding traffic constructed by listening to the instructions; however, it limits the capacity of the sector because of limited available voice bandwidth [Ker91]. One means of increasing overall capacity is to decrease the sector size. This increases the amount of administrative communication of log-on and log-off phrases of aircraft entering and leaving the sector but limit its effectivity [Air04].

In trans-oceanic operations, VHF communication is often not available because it is limited to line-of-sight. There voice communication needs to rely on High Frequency (HF) radio. The audio quality of HF is often far inferior to VHF communication making ATC communication difficult and limiting it to the minimum [DMA+97, Mas87].

AERONAUTICAL RADIO INCORPORATED (ARINC) offers a service to connect the aircraft with the AOC through voice radio communications. This service allows aircraft-AOC communication via VHF, HF, or Satellite Communications (SATCOM), almost anywhere worldwide. The close cooperation of the dispatcher and the flight deck crew can be used for flight optimization or disruption management; however, the communication is limited to operational control communication[17] [Fed13b, Aer10b].

Voice communication has proven ideal for solving tactical non-standard situations [Ker91]. More strategic applications, where a large amount of data needs to be exchanged between the stakeholders, such as the communication of complex 4D trajectories, requires different means of transmission that can transfer information without corruption or capacity issues. MUELLER ET AL. identified in an HITL study at the NASA Ames research center, that controllers were significantly more likely to issue time-saving flight plan amendments using Controller-Pilot Data Link Communications (CPDLC), compared to voice transmissions only [MMR+11].

2.3.2 Future air navigation system

The FANS is an ATM environment, including Communications, Navigation and Surveillance (CNS) hardware and software components, as well as Human Machine Interfaces (HMIs) and procedures to be used by controllers and pilots [FAN06]. Its operational concept was defined by the ICAO FANS committee [Int13b] to improve oceanic airspace operations through data link communication. The first product that used the FANS concept was developed by BOEING in the FANS 1 integration, later followed by a similar solution from AIRBUS the FANS A [Hon13].

[17] In the U.S. the FEDERAL COMMUNICATIONS COMMISSION (FCC) Code of Federal Regulations (CFR) Title 47 §87.261 states for the Scope of service [Fed13b]: "Aeronautical enroute stations provide operational control communications to aircraft along domestic or international air routes. Operational control communications include the safe, efficient and economical operation of aircraft, such as fuel, Wx, position reports, aircraft performance, and essential services and supplies. Public correspondence is prohibited.".

FANS 1/A

The FANS 1/A describes an operational integration of the ICAO FANS ConOps [Int13b]. The hardware architecture consists of Global Positioning System (GPS) as Global Navigation Satellite System (GNSS) for onboard positioning that is shared with ATC via Automatic Dependent Surveillance - Addressed (ADS-A) or ADS-C. CPDLC messages are exchanged between the pilot and controller using the existing Aircraft Communications Addressing and Reporting System (ACARS) protocol [Aer12c], which was developed for pilot-AOC communication. A message set as defined in ICAO *PANS-ATM* [Int07a] is used for CPDLC. The CNS infrastructure allows the assignment of RTA for waypoints along the route to merge traffic of crossing tracks. The onboard interface to the system depends on the aircraft vendor. On Boeing aircraft, the CPDLC communication interface is integrated into the Control Display Unit (CDU) where on Airbus aircraft a separate interface presents the CPDLC messages on a Data link Control and Display Unit (DCDU) that interfaces with the FMS. Once a CPDLC message is accepted it can be reviewed in the Multifunctional Control and Display Unit (MCDU) [Hon13].

Honeywell lists six advantages for operators to use FANS 1/A in oceanic airspace [Hon13]:

1. Reduced separation between airplanes
2. More efficient route changes
3. Satellite communication
4. No altitude loss when crossing tracks
5. More direct routings
6. Reduced user charges for using the FANS infrastructure

While providing operational benefits to operators in oceanic airspaces today, the capacity and safety of current FANS implementation are limited. Thus, advancements to meet these deficiencies are needed to allow the FANS-based CPDLC in continental airspace. These efforts will result in the FANS 2/B systems [Hon13, Rad04].

FANS 2/B

Further development of the FANS system is ongoing to support continental operations, and eventually TBO. The main difference to the FANS 1/A system is the use of the ICAO Aeronautical Telecommunication Network (ATN) [Int11a, Rad07], commonly via VHF Digital Link (VDL) Mode 2 [Rad12] or SATCOM, instead of the VHF ACARS messaging system. This increases the speed of the communication system and the reliability of the transmission. This system is currently deployed by EUROCONTROL as the Link2000+ program in the upper European continental airspace [Ghe09, Eur09]. Future applications include 4DTRAD and D-TAXI[18] [Eur08a, Rad07, Int12b]. The architecture includes a

[18] D-TAXI enables the receipt of taxi clearances and routings via CPDLC [LBW+10].

Communication Management Unit (CMU) [Aer10a], as illustrated in Figure 2.12, to host the ATN protocol and serve as centralized interface for all FANS subsystems [Eur09]. The HMI implementations remain the same as on FANS 1/A systems; however, the set of data link messages is expanded from the set defined in *ICAO PANS-ATM* [Int07a] to support more advanced applications. MUELLER ET AL. analyzed the effect of a trajectory negotiation using CPDLC messages and provided guidelines for efficient flight deck operations [ML08].

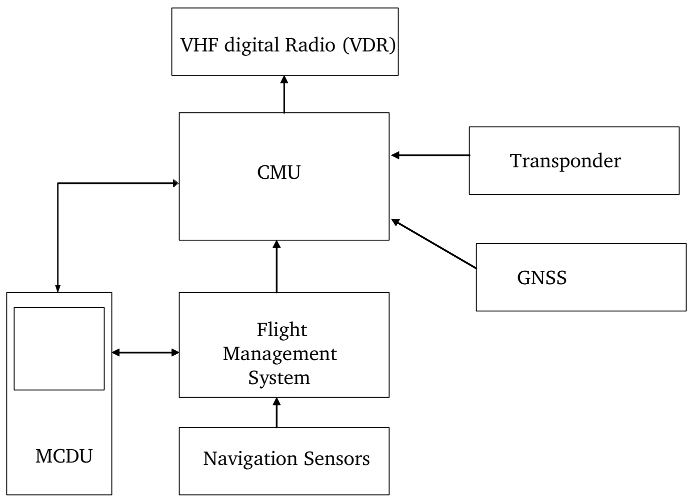


Figure 2.12.: FANS avionics architecture [Eur09]

2.4 Flight management systems

FMS were integrated into aircraft to support the flight crew in routine tasks of flight planning, navigation, flight control, and flight optimization [WB11, Aer94, Aer06]. This support in routine tasks of the FMS, and a display of information in an Electronic Flight Instrument System (EFIS), helped to eliminate the flight engineer from the cockpit[19] [Swe95].

MOIRE and SEABRIDGE [MS08] illustrate how the FMS integrates into the aircraft control system. As shown in Figure 2.13, the aircraft attitude is controlled by the Fly-By-Wire (FBW) system that acts on the aircraft's control surfaces and engines. The pilot can manipulate the commanded attitude through the pilot controls of yoke/side stick, pedals, thrust lever, or controls for secondary control surfaces: flaps, slats and speed brakes[20]. The trajectory of the aircraft is controlled by the Autopilot Flight Director System (AFDS). The pilot can enter a speed, heading, vertical speed, and commanded altitude in the Mode Control Panel (MCP)/Flight Control Unit (FCU) of the autopilot.

[19] The glasscockpit consisting of FMS and EFIS was first introduced in the late 1970s to early 1980s on the AIRBUS A300-600/A310 and BOEING 757/767 aircraft [Swe95].

[20] In military aircraft thrust vector control provides an additional means of control [MS08, ER92].

The Flight Mission is controlled by the FMS, which integrates an outer loop around the AFDS and FBW control systems. The flight crew defines the Flight Mission through input in the CDU/MCDU to define the mission objective in lateral and vertical domains within given constraints.

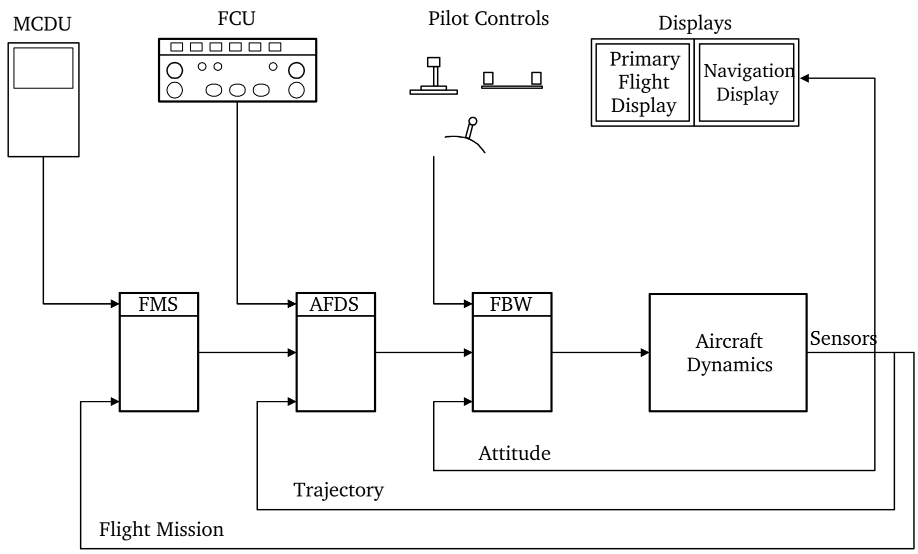


Figure 2.13.: Aircraft control loops: flight control, guidance and management after Moir and Seabridge [MS08]

The FMS allows the aircraft to follow a lateral route defined either by published waypoints or definition of latitude and longitude using the Lateral Navigation (LNAV) mode of the FMS, which calculates a commanded heading for the autopilot. The route is defined as a series of legs as specified in ARINC 424 [Aer11]. This 2D navigation capability became possible through the integration of Inertial Reference Systems (IRSs) onboard the aircraft to allow onboard locating of the aircraft. In today's aircraft, the locating is performed by a hybrid GNSS and IRS locating in an Air Data Inertial Reference System (ADIRS) [WB11].

To ensure adherence to constraints during descent, the Vertical Navigation (VNAV) mode allows 3D navigation that considers altitude constraints. VNAV has two modes: VNAV path and VNAV speed. In path mode, the guidance reduces the vertical deviation to the reference to a minimum while allowing deviations in speed. The handling in speed mode is conversely ensuring maximum adherence to the nominal speed while allowing flexibility in the vertical path [WB11].

In modern integrations, the FMS not only allows the aircraft to follow a precise lateral route[21] or vertical navigation[22], but also optimizes the overall costs for the flight [Air98].

[21] Including RNP procedures with Radius to Fix (RF) legs [HCS08, Rad03].

[22] Including the calculation of Optimum Profile Descents (OPDs) [Int10].

2.4.1 Cost optimization

According to AIRBUS [Air98], the direct operating costs of a flight consist of fixed costs[23], time-related costs[24] and fuel costs. The costs and its components are plotted over the Mach number in Figure 2.14. At M_{ECON} the direct operating costs reach a minimum. The concept of the Cost Index (CI) is introduced to reference M_{ECON}, which is influenced by the airline's cost structure, fuel prices, and environmental conditions.

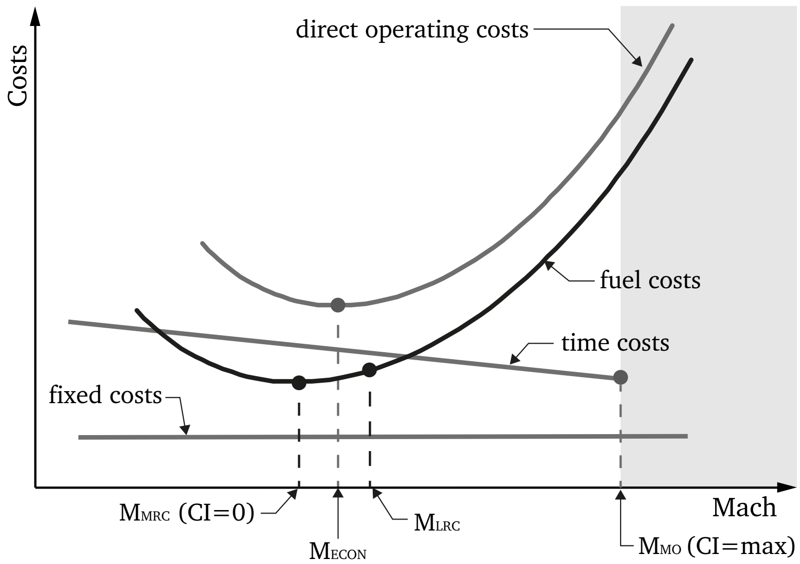


Figure 2.14.: Direct operating costs over Mach number after SCHEIDERER [Sch08]

The CI relates the time-based costs to the fuel-based cost (see Equation 2.2) and is scaled depending on the FMS manufacturer. CI=0 corresponds to the minimum fuel consumption and M_{MRC}. CI=max[25] corresponds to a minimum flight time (M_{MO} minus a margin), where the margin is defined by the aircraft type [Air98, Boe07]. Before the introduction of the CI, M_{LRC} was often used as economic speed which is defined as the speed at which 99% of the specific range of M_{MRC} can be achieved. The 1% increase in fuel consumption results in 3 to 5% higher cruise velocities [Boe07**?**]

$$CI = \frac{C_{Time}}{C_{Fuel}} \tag{2.2}$$

Each airline uses the CI differently. It can be used as a static value that was once optimized for boundary conditions at that time, or optimized for each route with updates in fuel and operational costs [Air98]. The costs of a flight highly depend on arriving on-time at an

23 Fixed costs are independent of time and include the airline's administration and overhead, independent of flight operations.

24 Time-related costs include: hourly maintenance costs, flight crew and cabin crew costs, marginal deprecation or leasing costs, and direct maintenance costs [Air98].

25 Depends on the FMS type and can vary between 99 and 9999 [Air98].

airport[26]. This makes setting the speed to meet an RTA, rather than flying at the most efficient CI, the most cost-efficient choice for the airline in certain scenarios.

2.4.2 4D functionality

Many FMSs today[27] are equipped with RTA functionalities to enable the timely arrival at one waypoint along the route. The guidance logic of a SMITHS/GE FMS is depicted in Figure 2.15. Temporal deviation "dead bands" are defined to allow reaction to disturbances

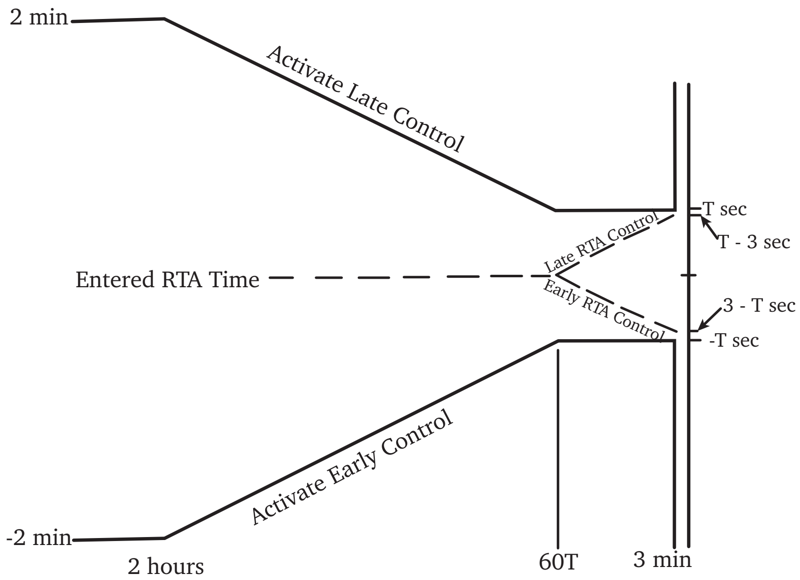


Figure 2.15.: Time to RTA waypoint after DEJONGE [DeJ92]

while minimizing throttle activity. The "deadband" allows a deviation of ±2 minutes up to 2 hours before the RTA is reached which is then linearly reduced to the defined margin[28], 60 times the margin (60T) before the RTA[29]. Three minutes before reaching the RTA-constrained waypoint, the RTA logic stops to perform speed changes needed to meet the constraint of avoiding larger speed fluctuations [DeJ92].

According to DE SMEDT and BERZ [SB07], 40% of flights in Europe are equipped with a FMS to meet an RTA enroute with a precision of 30 seconds, but only 11% of flights can

26 Arriving at the destination with delay, costs in fuel, maintenance, fleet, crew, passengers and reactionary costs occur. Arriving early at a destination is also not economical, as aircraft utilization could be optimized [Eur11].

27 The following aircraft are equipped with RTA functionalities: AIRBUS aircraft with 2nd generation FMS (HONEYWELL Pegasus or THALES-GENERAL ELECTRIC (GE)), BOEING 737Next Generation (NG) (software U7.1 or later), BOEING 757/767 with Honeywell Pegasus FMS, BOEING 777, BOEING 747-400 with FANS 1A (s/w load 15), MCDONNELL DOUGLAS (MD)-90 / MD-11 with HONEYWELL Pegasus FMS [Sme12].

28 Between ±3 seconds and up to ±30 seconds [DeJ92].

29 For a 60-second margin, for example, the dead band is reduced one hour before the RTA.

fulfill an RTA with an accuracy of 6 seconds in cruise, climb, and descent with GPS time as the reference.

TELLER [Tel11] performed a HITL simulation assessing the usability of FMS RTA functionalities. The experiment showed that the BOEING 737NG GE FMS demonstrated a reliability of 90% in meeting an RTA within the specified accuracy. The A320 HONEYWELL Pegasus FMS also demonstrated 87% compliance to the RTA within specified tolerances. Manual RTA operations using a HONEYWELL Primus Epic FMS have not shown acceptable accuracy in meeting the assigned RTA. Although the RTA functionality of modern FMS proved to be robust and reliable in automatic integrations, it is rarely used in operation. TELLER [Tel11] states that the negotiation of a RTA via voice showed high acceptance but increased the voice communication and would be problematic in busier conditions than tested in the experiment. While the tools needed to negotiate the RTA via CPDLC are not in place on the ground or onboard the aircraft for continental operation, their integration is planned with the deployment of I-4D.

2.5 Electronic flight bags

With an aircraft life expectancy of 20-30 years [Jia13], new technologies are difficult or connected to high costs to integrate into aircraft already in service. The outfitting with EFBs provides an opportunity to equip these aircraft with updated functions at lower cost than an update to the aircraft's primary avionics. One example for such a feature is the Airport Moving Map (AMM), where many aircraft are equipped with an EFB solution, but only the latest generation of aircraft[30] is equipped with a front panel integration.

According to the 2012 IATA avionics survey [O'C12], 20.5% of the aircraft were equipped with EFBs and 11.7% of the aircraft were equipped with Flight Crew Portable devices[31]. In addition, McKENNA [McK11] states that many operators are planning to invest in EFB systems to support NextGen and SESAR operations. EFBs can be categorized into three hardware classes and three software types that allow different integrations and functions. Guidance for the categorization into the classes and types is given by the FAA in *Advisory Circular (AC) 120-76B [Fed12a]* and by the EUROPEAN AVIATION SAFETY AGENCY (EASA) in *Temporary Guidance Leaflet (TGL) 36* [Eur04]. A summary of this guidance is provided in the following.

2.5.1 Hardware classes

In recent years, aircraft operators demanded to integrate the developments of tablet computer on the consumer electronics market as EFB devices on their flight decks. This demand resulted in an update to the AC 120-76 [Fed12a] in June 2012 to include guidelines for the use of Personal Electronic Devices (PEDs) as Class 1 or Class 2 EFB devices. The

[30] BOEING 787 & AIRBUS A380 [Fos12].

[31] The survey's sample size included 4874 aircraft of 283 fleets [O'C12].

change lead to a diversification of EFB types. In general, the classification of EFBs differs by their mounting and connectivity with aircraft systems.

Class 1: The EASA defines Class 1 EFBs in TGL 36 as [Eur04]:

> "...*portable, Commercial off-the-shelf (COTS) devices that are part of a pilot's flight kit and are not mounted to the aircraft.*"

An easy integration into the flight deck and no FAA or EASA approval for design, production, or installation required are the main advantages of a Class 1 EFB [Fed12a]. The category includes laptop computers that are used by the flight crew during preflight for mass and balance applications. Class 1 devices can also be used to display type B applications during "critical phases of flight"[32] if "secured and viewable"[33] [Fed12a].

Class 2: The EASA defines Class 2 EFBs in TGL 36 as [Eur04]:

> "...*typically mounted to the aircraft by a mounting device and may be connected to a data source, a hardwired power source, or an installed antenna.*"

The advantage of a Class 2 EFB is the mounting to the aircraft, power supply from the aircraft and data connection to the aircraft[34] systems. The data connection allows information (e.g. aircraft state information) to be retrieved on the EFB and used for AMM applications [Fed07a, Fed11a]. Typical examples are retrofitted EFBs on specialized hardware in aircraft originally designed without such systems. One example of such integration is a NavAero t-Pad [Aer09]. Also, Apple iPad mounts have received FAA STC approval as Class 2 EFBs [pen13].

Class 3: The FAA defines Class 3 EFBs as [Fed12a]:

> "...*EFBs installed in accordance with the applicable airworthiness regulations.*"

Differentiating from the first two classes, Class 3 EFBs require an airworthiness approval for the entire EFB system[35] and the hardware needs to be certified according to DO-160G [Rad10, Fed12a]. Examples are the fully integrated EFBs of the Boeing 737NG, 747-400/-8, 777 and 787 [Eur14] as well as the Onboard Information System (OIS) onboard the Airbus A380 [Boa08].

[32] The definition of "critical phases of flight" used in AC 120-76B [Fed12a], is defined in Part 121.456 (c) [Fed81] as: "[...] all ground operations involving taxi, take-off, and landing, and all other flight operations conducted below 10,000 feet, except cruise flight."

[33] One application is the display of departure and approach tiles on an Apple iPad used as a kneeboard [Spo13].

[34] These functions require a Supplemental Type Certificate (STC) according to FAA Order 8900.1 [Fed07b, Fed11a].

[35] Commonly received through a STC.

2.5.2 Software types

The Software running on EFBs is categorized into three[36] types that differentiate the applications by their scope and required approval process.

Type A: The EASA defines type A applications as [Eur04]:

> "*...software applications [that] include pre-composed, fixed presentations of data, currently presented in paper format.*"

Type A applications can run on any EFB hardware class and require only operational and no airworthiness approval. The applications include manuals, reports, and logs such as the Flight Operating Manual (FOM), Minimum Equipment List (MEL), and graphical Notice to Airmen (NOTAM) [Eur04, Fed12a].

Type B: The EASA defines type B applications as [Eur04]:

> "*Type B software applications include dynamic, interactive applications that can manipulate data and presentation.*"

As for type A applications, no airworthiness approval is required for type B applications and the software can reside on any EFB hardware. Type B applications are intended to be used during "critical phases of flight". Typical applications include, but are not limited to, Aircraft Flight Manuals (AFMs), mass and balance calculations, and precomposed or dynamic interactive electronic aeronautical charts, with the limitation that no ownship symbol is permitted to be shown while inflight [Eur04, Fed12a].

Type C: The FAA describes type C applications as [Fed12a]:

> "*...those found in avionics, including intended functions for communications, navigation, and surveillance, that require FAA design, production, and installation approval.*"

All applications have to be compliant to the specifications of Radio Technical Commission for Aeronautics (RTCA) DO-178C [Rad11] or other acceptable means [Fed12a, Fed11a]. A failure of the application is classified as "major hazard" or higher, according to the specifications of RTCA DO-178C [Rad11, Fed12a]. Type C applications can be hosted on class 2 or class 3 EFB hardware[37]. FAA Order 8900.1 [Fed12b] differentiates type B and type C application by the depiction of an ownship symbol inflight and if the application provides information to any aircraft system. However, any application that cannot be categorized as type A or type B, and is hosted on EFB hardware, is categorized as a type C application.

[36] The EASA TGL 36[Eur04] differentiate only between type A and type B applications, as type C software requires a certification according to DO-178C [Rad11].

[37] The depiction of an ownship symbol inflight cannot currently be authorized on a class 2 device [Fed12a].

2.6 Research gap

Much research has been performed in the field of TBO. From this research, multiple technological enablers have matured, and will now be implemented in the SESAR and NextGen programs. Where the implementation steps for the 4DTRAD service are well defined, the research projects focusing on a full 4D or continuous trajectory exchange between the stakeholders are lacking the transition from current operations to the envisioned concepts. Table 2.1 provides a summary of various capabilities of exemplary

Table 2.1.: Overview of addressed issues in research projects

Capability/Project	4DTRAD [Eur08a]	CATS [GGCR08]	PHARE [vGS99]	WESTPHAL
trajectory description	I-4D	full 4D	continuous	full 4D continuous
time horizon	short term	medium term	long term	short term medium term
aircraft-ANSP data link	✓	✓	✓	-/✓
controlled time of arrival	✓	✓	✓	✓
sector capacity management	-	✓	✓	✓
separation management	-	-	✓	-/✓
aircraft-AOC data link	-	-	-	✓
retrofit capability	-	-	-	✓
flight trial validation	✓	-	✓	✓

research projects[38]. All concepts have the expanded use of aircraft-ANSP data link to share and negotiate trajectories in common. The initial benefits of TBO may be realized in the TCA. All concepts share the assignments of controlled times of arrival at waypoints in the TCA to merge arrival streams. Through a precise contracted definition of the trajectory from gate-to-gate, the information can be used on the ground to manage the sector capacity, as precise fly-over times are known in advance. This process is supported by all concepts but 4DTRAD, where predictability is increased through the downlink of ETAs, but not contracted. The advanced concepts using a continuous trajectory description to define a "safety bubble" or "tube", enable the use of trajectories to ensure separation from other aircraft, through a deconfliction in the trajectory generation process.

The research presented in this thesis is focusing on the integration of the AOC in the onboard trajectory management process. A trajectory that satisfies the needs of all stakeholders can only be negotiated by involving all stakholders including the AOC. One of the key findings of the third CATS HITL experiment was the necessity of an aircraft-AOC data link connection for trajectory negotiation, which was limited to voice communication during the trial [GGR10b]. In addition, the investment to equip the aircraft of an airline with TBO-capable avionics should be kept to a minimum, to enable widespread TBO installation and reinforce a business case for the airline. Therefore, this thesis fo-

38 The list is non-exclusive for both the list of projects and the list of capabilities.

cuses on the integration of the Trajectory Management System (TMS) into the flight deck, on a connected and integrated EFB platform. As for all research focusing on a short- to mid-term integration into operation, the pilot remains the main decision maker on the flight deck, taking over some of the management tasks from the Air Traffic Control Officer (ATCO). Therefore, the TMS will be implemented as decision support system. To develop such a system, knowledge of the cognitive ergonomics is needed to ensure the developed system is usable by the pilot. The following section provides an overview of the cognitive ergonomics effecting onboard decision support tools.

3 Conception of an onboard retrofit trajectory management system

This chapter applies the information collected in the previous chapter on the Air Traffic Management (ATM) system and its expected changes to Trajectory-Based Operations (TBO). First, the operational environment, for the system is specified. From the defined research objective, a decision support system with three functionalities is derived, that requires solutions for the trajectory negotiation, monitoring, and guidance. The trajectory negotiation function provides the pilot with a toolset to negotiate trajectories with the Airline Operations Center (AOC) and Air Traffic Control (ATC) and display these graphically on a chart for the pilot. A tool is described to ease the monitoring of the adherence to temporal constraints along the trajectory. This chapter also presents four different integration approaches for flight guidance control loops.

3.1 Operational environment

Three operational environments (Initial 4D (I-4D), full 4D, and continuous trajectories) have been laid out so that TBO can be applied as a tool to solve challenges of today's ATM system[1]. From these operational environments, the applicable scenario for which the onboard Trajectory Management System (TMS) will be conceptualized has to be chosen. No sharp boundary can be drawn between the described operational environments. Instead, tools are described to solve specific challenges of the ATM system. The chosen operational environment should adhere to one environment established in research, but may deviate where beneficial.

The Contract-based Air Transportation System (CATS) Concept of Operations (ConOps) [Eur10], with the principles of Target Windows (TWs), and a Contract of Objectives (CoO) can be applied for a gate-to-gate trajectory description that considers the goals of all stakeholders (AOC, Air Navigation Service Provider (ANSP) and the flight deck crew). I-4D can be categorized as a subset of these full 4D operations and would also be supported by a TMS using the CATS ConOps. Therefore, the CATS concept is chosen as operational environment and is expanded for a continuous trajectory arrival guidance method that could allow the separation and spacing of aircraft in the Terminal Control Area (TCA). This allows the evaluation of an onboard retrofit TMS with all trajectory definitions, while allowing the flexibility for an economic trajectory optimization within the contracted TWs for most of the flight.

[1] Compare to Section 2.2.

The connectivity of the TMS with the aircraft avionics has a direct effect on the operational environment, in which it can support operations. Therefore, different integration levels are considered, ranging from a non-integrated class 1 Electronic Flight Bag (EFB), up to a fully integrated scenario with an EFB class 2/3 and connectivity to AOC, ATC and the Flight Management System (FMS). Within prior concepts and evaluations (for example in the CATS Human-in-the-Loop (HITL) evaluation [GGR10a]), a missing AOC data link was criticized. The concept presented in this thesis will integrate AOC data link capabilities into the retrofit TMS. As the retrofit TMS The TMS shall be designed as decision support system.

3.2 Design of a decision support system

A human-centered design approach is taken for the design of the TMS as decision support system. This approach focusses on providing the pilot sufficient Situation Awareness (SA) for decision making. In the following an overview of human-centered design is given and the concept of SA detailed out further. From the SA concepts and information requirements the functionalities of the TMS are derived.

3.2.1 Human-centered design

In the past, systems were developed by technology-centered design. Each system was designed separately from other systems to perform a task. An interface for the operator was then developed to inform the operator of the systems' state and performance. The traditional development of an aircraft cockpit is a perfect example for technology-centered design. As systems and functions increased, so did the number of displays in the cockpit. In the 1970s, the single displays and gauges where replaced by an Electronic Flight Instrument System (EFIS)[2]. This did not limit the information, but combined and distributed it on multiple pages and menus. The vast amount of available data led to an *information gap*, depicted in Figure 3.1, as little information was needed, that information had to be found, sorted, integrated and processed. It ultimately led to human error and accidents, because the needed information was not available, or required high mental workload to process by the operator. Trying to automate tasks to avoid these accidents was not successful and led to increased complexity and even more accidents, as the operators were not fully aware of the situation, or were unable to perform tasks when automation degraded [EBJ03, End95].

To avoid these mistakes in system design, Endsley et al. propose an approach to a user-centered design that relies on three principles [EBJ03]:

1. Organize technology around the user's goals, tasks, and abilities.
2. Organize technology around the way users process information and make decisions.

[2] Compare to Section 2.4.

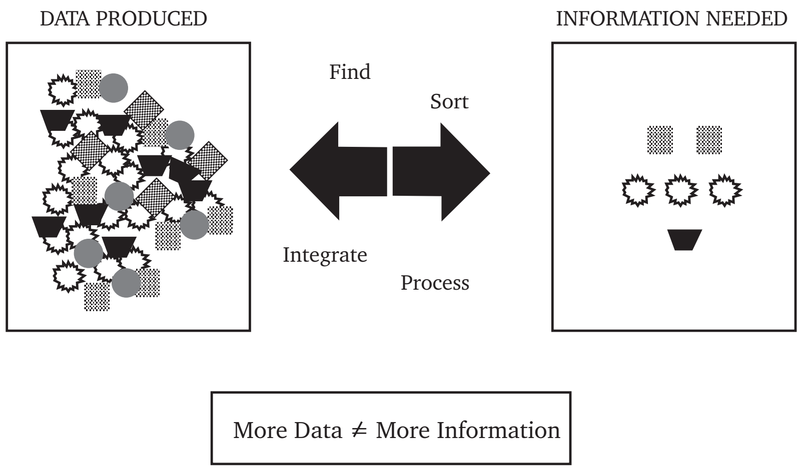


Figure 3.1.: Data produced compared to information needed after ENDSLEY ET AL. [EG00]

3. Structure the technology to keep the user in control and aware of the state of the system.

To apply user-centered design, ENDSLEY ET AL. propose a SA-oriented design [EBJ03]. This approach requires a detailed understanding of SA and its integration in the decision making process.

3.2.2 Situation awareness

An understanding of the decision making process requires, the decision makers to have an understanding of how awareness in dynamic situations is created.

ENDSLEY marked the term of *Situation Awareness* and defined it as [End88a]:

> "*...the perception of elements in the environment within a volume of time and space, the comprehension of their meaning, and the projection of their status in the near future.*"

The definition identifies three levels of SA [End95]:

Level 1 SA: Perception of the Elements in the Environment The first phase of SA is to perceive status, attributes, and dynamics of elements in the environment. A Pilot perceives information such as aircraft state information or route information that is relevant for a safe flight and needed for a certain task [EFJ+98]. JONES and ENDSLEY analyzed that 77.4% of errors were the result in lack of Level 1 SA where information was misperceived or not perceived at all [JE96].

Level 2 SA: Comprehension of the Current Situation The current situation is then comprehended from the perceived elements assisted by mental models. An unexperienced pilot may perceive required elements as well as an experienced pilot but may not reach the same level of comprehension [EFJ+98] because of a lack of mental models for the assumed system behavior. 21.1% of errors were related to a missing or incorrect comprehension of the situation. These errors were often the result of a lack of, or incomplete, mental models[3] [JE96].

Level 3 SA: Projection of Future Status With an understanding of the current situation and mental models, the current situation can be projected to a future state [EFJ+98]. Only 1.5% of errors where the result of insufficient projection [JE96].

These three levels form the SA that is limited to "*the environment within a volume of time and space*" therefore, it is a continuous process with the environment changing over time in a dynamic system.

SA is linked to decision making according to ENDSLEY's model of dynamic decision making. As illustrated in Figure 3.2, SA provides the steering input to the decision making

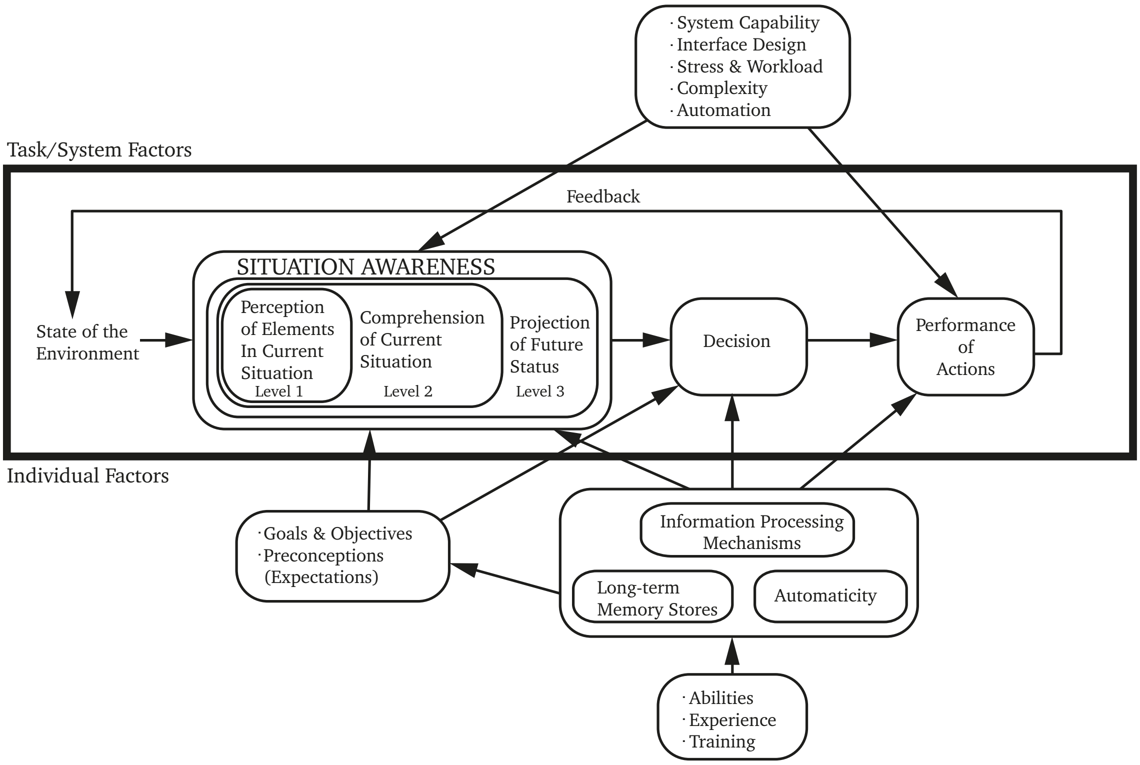


Figure 3.2.: Situation awareness model in dynamic decision making after ENDSLEY [End95]

process, which is also influenced by task/system and individual factors that influence the SA. Actions are performed as a result of the decision making process. These actions change the state of the environment. The new state is then perceived, comprehended and projected as updated SA. Although SA, decision making and performance are separate processes, the preceding process outcome is fed into the following process [End95][4].

3 See Appendix A.2 for a detailed list of SA error causes [JE96].

4 More information on the task and system factors influencing the process can be found in Appendix A

3.2.3 Functions of a Trajectory Management System

Functionalities and features should never be implemented as an end in themselves, but only as tools to accomplish goals. The goal of an onboard TMS is, to create a common understanding of a trajectory and its constraints among the involved stakeholders, execute it by guiding the aircraft along the trajectory, and to provide the means to monitor the adherence thereof. Endsley et al. [EFJ+98] categorized the SA information requirements of commercial pilots into the three level of SA. This categorization can be applied to TBO and summarized as it is done in Table 3.1. The three functionalities of trajectory negotiation, monitoring, and guidance can be categorized according to the three SA levels to which they provide the pilot information. The trajectory negotiation function requires transient information of the currently planned trajectory for the pilot. For a renegotiation inflight, additional information on the aircraft state and the cost/benefit of the planned trajectory revision is important. The trajectory monitoring function provides the pilot with information on the deviations to the planned trajectory as well as with projections of the performance relative to the planned trajectory that evolves over time. For the trajectory guidance, the pilot requires input on control information.

Table 3.1.: Pilot SA information requirements for TBO (with information from Endsley et al. [EFJ+98])

<table>
<tr><th>Level 1 SA</th><th>Level 2 SA</th><th>Level 3 SA</th></tr>
<tr><td>• planned trajectory
• aircraft state</td><td>• deviations to trajectory
• required control inputs
• cost/benefit of trajectory revision</td><td>• projected trajectory</td></tr>
<tr><td colspan="2">negotiation</td><td></td></tr>
<tr><td></td><td colspan="2">monitoring</td></tr>
<tr><td></td><td>guidance</td><td></td></tr>
</table>

3.3 Trajectory negotiation

The first function of the TMS to be conceptualized is the trajectory negotiation. Without a shared understanding of the trajectory that accurately represents the objectives of all stakeholders no benefit of TBO can be realized. Not only does the information have to be shared between the systems of the stakeholders, but it must be shared also from the systems to the human operator as decision-maker in the ATM system. Two forms of inflight trajectory negotiation can be differentiated. First, the initial briefing is created by the AOC to familiarize the pilot with the planned trajectory and the CoO. Second, the revision briefing which is performed when the CoO is revised. There, not only the familiarization with the trajectory but also an evaluation whether the CoO meets the airlines operational and economic objectives is required for tactical negotiations.

- **strategic negotiation** describes any negotiation of the trajectory that influences a large part of the planned trajectory. It is applied for the initial negotiation of the Reference Business Trajectory (RBT), but also for larger revisions e.g. due to strategic Weather (Wx) avoidance.

- **tactical negotiation** is performed when one or few objectives of the trajectory needs to be revised such as for traffic avoidance. It can include one or few Trajectory Change Points (TCPs)[5] constraint revisions or a smaller tactical re-routing. Tactical negotiations are, in general, more time-sensitive than strategic negotiations, and may therefore, be replaced in urgent cases by a voice negotiation of the trajectory.

The following Sections show how these trajectory negotiations are communicated among the stakeholders and how their information is evaluated by the pilot.

3.3.1 Communication

Wherein the CTA/ATC System Integration Studies (CASSIS) project [Mem09] the assignment of Required Time of Arrivals (RTAs) was performed via voice communication, the communication of multi-objective full 4D CoO via voice communication is not feasible with the given capacity of the audio channel. Therefore, data link connectivity from the aircraft to the AOC and ATC should be used, to share the understanding of the planned trajectory, and to negotiate the needed changes.

Airline communication

The AOC is the responsible entity to plan and monitor efficient and economic operations of the entire airline fleet. The constraints imposed by ATC, to permit the expedited flow of traffic, have to be within the economic boundaries for each flight. The AOC has the overview of the entire airline fleet, and interdependencies between flights and information on airport resources, so the decision for an economic flight is best taken at the AOC.

To communicate a trajectory with the aircraft, an Operational Flight Plan (OFP) in Aeronautical Radio Incorporated (ARINC) 633 [Aer12b] format, enhanced with the constraints imposed by ATC and terminal procedures for departure and approach, provides all information to communicate the CoO of the flight. In addition, economic constraints such as a minimum and maximum flight Cost Index (CI), can be defined and transmitted from the AOC to the aircraft[6].

[5] A TCP can be a navigation waypoint or operational waypoint, resulting in a track, altitude or speed change, such as the Top of Descent (TOD). Compare to Section 2.2.2 for details on the constraint types which can be imposed in a full 4D trajectory description.

[6] See Section 3.4.2 for their usage in the time constraint depiction.

Air traffic control communication

ATC is responsible for preventing collisions between aircraft in controlled airspace and to expedite the flow of traffic [UDoT12]. In the CATS concept [Eur10], ATC performs these tasks by assigning tactical revisions to the planned trajectory, changing the CoO. This tactical negotiation is performed between the aircraft and ATC. Onboard the aircraft, specific parameters are required to determine if the revision to the planned trajectory is feasible, and if the revision meets the economic requirements of the airline. The AOC and ATC coordinate strategic revisions, in advance, before uplinking them to the aircraft, to meet the airline's flight objectives.

Any stakeholder can initiate a revision of the trajectory at any time before or during the flight execution, with any other stakeholder, if changed conditions are not reflected in the CoO. In any case, the final agreed revision needs to be uplinked to the aircraft, where it is briefed and reviewed for operational and economic feasibility. Then the flight deck crew either accepts or declines the new CoO, and begins to follow any new, accepted guidance, if accepted. The pilot required a detailed briefing of the trajectory, and any revisions to it, to make a decision on the CoO.

3.3.2 Briefing

An adequate briefing is crucial for the safe execution of the flight. The briefing of a trajectory allows the pilot to create an understanding of the contracted objectives of the flight, and are an opportunity for the pilot to evaluate whether these objectives comply with the airline's operational constraints. This approach assists the pilot in understanding actions taken by the guidance system and in monitoring the performance of the guidance. The pilot's level 1 SA is enhanced, by providing static information of the objectives. As Jones and Endsley identified, the majority of errors (77.4%) derive from a lack of Level 1 SA [JE96][7].

Initial briefing

Before take-off, the pilot performs an initial briefing, for familiarization with the planned flight and its objectives. Endsley et al. list the briefing information for a flight plan as level 1 SA information for today's operation of commercial pilots [EFJ+98]. To allow TBO in addition to the information compiled for the current day, the pilot requires additional information on the constraints of the trajectory.

For the description of a trajectory as CoO as in the CATS concept [Eur10], the pilot needs information on constraints in altitude, speed, and RTA at TCP, along the trajectory. A conventional briefing includes the planned cruise Flight Level (FL) and the Scheduled

[7] Compare to Section 3.2.1 on SA.

Time of Arrival (STA). While the number of constraints to be briefed by the pilot is increasing, for the required information for the pilot on time and altitude targets, the number of speed constraints is not expected to increase with the use of TBO.

- **altitude constraints** provide vertical separation of aircraft. In the TCA, the altitude may be subject to more restrictions where as in cruise larger flexibility would prove beneficial for the aircraft to fly at the most efficient FL.
- **time constraints** are assigned at TCPs by ATC, to manage aircraft flows and sector capacities[8]. Additional time constraints may be imposed by the AOC to ensure a timely arrival of the aircraft without considering economic measures.
- **speed constraints** are redundant to RTA constraints at given environmental conditions. Speed constraints should be minimalized as much as possible. However, these constraints do provide a tool, especially in the TCA, to ensure operation within the aircraft envelope, such as limiting the bank angle at turns on terminal procedures.

In addition to the trajectory briefing, the pilot's pre-flight preparation should include a Wx check, Notice to Airmen (NOTAM), and aircraft performance briefing [UDoT12].

Revision briefing

The briefing of a trajectory revision occurs when a trajectory was renegotiated during flight in the process of renegotiation. As the renegotiation occurs in a dynamic situation, in addition to the revised level 1 SA information, more information is required by the pilot to assess the situation. The effect of the applied revision to level 2 and level 3 SA information needs to be identified and comprehended by the pilot. For this, the pilots require a list of all planned flight TCPs, constraints attached to these TCPs, their influence on the planned flight, and the current aircraft state information.

A trajectory is described through large ammount of information valid at georeferenced locations. Therefore, it is assumed that the briefing of the negotiated trajectories on a chart display provides a higher degree of SA, to the pilot, than the briefing of Aircraft Communications Addressing and Reporting System (ACARS), or Controller-Pilot Data Link Communications (CPDLC) messages, with the same trajectory information as text on presented on the Multifunctional Control and Display Unit (MCDU)/Control Display Unit (CDU) or Data link Control and Display Unit (DCDU).

3.4 Trajectory monitoring

Airline pilots do not regularly monitor temporal adherence of a flight to constraints. Where as information such as lateral and vertical position or speed can be directly influenced by the pilot, the time at a TCP along the route is the result of the integration of

[8] Compare to Section 2.2.

Ground Speed (GS) along the route. Thus, the pilot needs speed guidance information in order to meet the temporal objectives of the trajectory without deviating from a given lateral route. In addition, the pilot needs information on the temporal performance relative to the aircraft flight envelope or economic operation objectives, to judge whether a trajectory objective is achievable. For this, level 2 and level 3 SA information is required for an overview of the current trajectory deviation and the projected trajectory[9].

To monitor the trajectory adherence, this thesis proposes a method to display both flight envelope and economic performance information integrated into a chart display when a temporal constraint is present[10]. The proposed display is an adaption of a display from Ballin et al. [BWAP08] to monitor the adherence to a continuous 4D trajectory, shown in Figure 3.3. The temporal RNP value of the continuous trajectory is transformed into

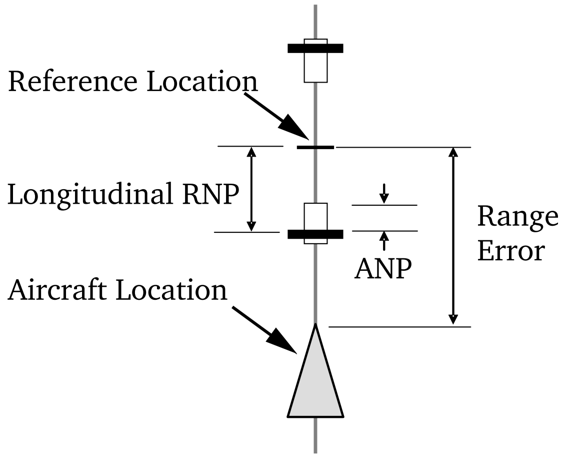


Figure 3.3.: Temporal RNP display after Ballin et al. [BWAP08]

a longitudinal RNP value that can be displayed on a chart relative to the estimate time of reaching the constrained TCP. In addition, the chart display plots the ideal reference location and the Actual Navigation Performance (ANP) are plotted. With these the range error can be defined as the distance from the current aircraft location to the reference location. DeJonge and Klooster [DK12] patented an adaption of this display to indicate the aircraft performance achieving an RTA with given accuracy. They describe a display that translates the difference between RTA and Estimate Time of Arrival (ETA) for a constrained display into an along track distance by multiplying the time difference with the GS and displaying the required accuracy of achieving the RTA, adjusted for distance to the constrained TCP, as the RTA time box from this point.

The monitoring display used in this thesis - named Precision Aircraft Control enhancing Route (PACeR) - applies not only the current aircraft performance, but to predictions along the trajectory, links the RTA time box graphically to the lateral trajectory, and ex-

[9] Compare to the information classification in Section 3.1.

[10] Barraci and Wiesemann describe a similar display not limited to a given lateral and vertical trajectory, depicting flyable areas to the pilot for given optimization objectives [BW13].

pands the idea through the integration of a CI to monitor economic operations. Because of larger resulting allowed longitudinal deviations, using the full 4D trajectory description, the ANP is likely neglectable, and is therefore not part of the PACeR depiction. The reference location is not plotted, since no guidance information should be given, but only assistance in monitoring the trajectory adherence, should be given with the PACeR. The following sections present the two complementary PACeR integrations for flight envelope and economic limitations. The PACeR allows the pilot to interpret if a trajectory objective is within the flight envelope of the aircraft and whether or not this objective can be obtained within given economic constraints of the airline. This information can help to determine when a trajectory renegotiation needs to be initiated onboard for an already defined process.

3.4.1 Flight envelope monitoring

The concept from Ballin et al. uses the planned GS for the segment to calculate the allowed longitudinal deviations. To provide the pilot information whether a time constraint can be fulfilled, the flight envelope is the limiting factor[11].

The most simplistic calculation of the reference location of an aircraft for a I-4D or full 4D trajectory description is shown in Equation 3.1, where s is the stretch to the reference location of the aircraft, $d_{TCP_{constraint}}$ the distance of the constrained TCP to the beginning of the stretch, GS the aircraft planned GS and $t_{constraint} - t_{current}$ the available time before reaching the constraint [WBKS13]. This calculation assumes a constant GS along the segment of the trajectory to the next constraint.

$$s = d_{TCP_{constraint}} - GS \cdot (t_{constraint} - t_{current}) \tag{3.1}$$

However, the aircraft GS and the minimum and maximum constraint time can vary as well as the TCP to which they apply. This results in the calculation of a minimum and a maximum PACeR distance[12], as illustrated in Figure 3.4. The minimum ($V_{cr,min}$) and maximum ($V_{cr,max}$) True Airspeed (TAS) define the minimum and maximum achievable GSs at given wind conditions in cruise. The values for these speeds are retrieved either through an interface to the aircraft's FMS or through performance calculations such as using the European Organisation for the Safety of Air Navigation (EUROCONTROL) Base of Aircraft Data (BADA) model[13] [Eur12b].

11 Compare to DeJonge and Klooster [DK12].

12 As the most constrained TCP does not have to be identical for the minimum and maximum limit, the index n is used for the TCP limiting s_{max} and the index m for the TCP limiting s_{min}. Compare Westphal et al. [WBKS13].

13 See Appendix B for definition and calculation at given environmental conditions using the EUROCONTROL BADA model.

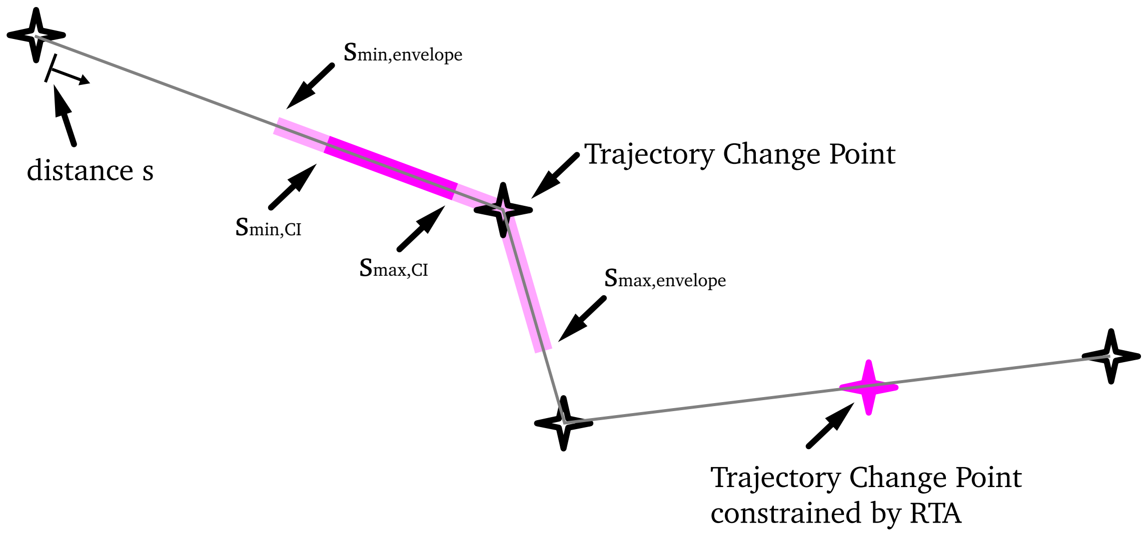


Figure 3.4.: PACeR distances

$$s_{max,envelope} = d_{TCP_n} - \int_{t_{current}}^{t_{TCP_{n,min}}} \left(\vec{V}_{cr,min}(t) + \vec{V}_{wind}(t)\right) dt \tag{3.2a}$$

$$s_{min,envelope} = d_{TCP_m} - \int_{t_{current}}^{t_{TCP_{m,max}}} \left(\vec{V}_{cr,max}(t) + \vec{V}_{wind}(t)\right) dt \tag{3.2b}$$

The GS of the aircraft is a function of time, because the wind speed and TAS are functions of space and time. The covered distance within a time interval can be calculated through integration of the GS over time, along the trajectory, as is shown in Equation 3.2.

Over time the PACeR area decreases, indicating the reduction of longitudinal flexibility in order to meet the constraint. During a nominal flight, the aircraft position should always be contained in the area by $s_{max,envelope}$ and $s_{min,envelope}$. If the aircraft position is outside of these limits, the aircraft cannot maintain the contracted trajectory objectives, requiring the pilot to renegotiate the trajectory.

3.4.2 Economic monitoring

Operating an aircraft to both ends of the flight envelope, in order to meet a time constraint, is not economical. Therefore, civil commercial flights require an additional measure for the pilot to determine the economic achievability of fulfilling an imposed time constraint.

In today's aircraft, the CI provides an onboard cost optimization tool[14]. The same principle can help to determine if a time constraint is economically feasible for the airline.

[14] Compare to Section 2.4.1, Airbus [Air98] and Boeing [Boe07].

However, more flexibility is needed as one CI determines an ideal speed at given environmental conditions. The CI range is proposed as an economic measure, that combines the flexibility to meet temporal constraints with a limitation of a resulting increase in costs to meet the constraints. The range can vary between airlines, flights and can be adapted at any time, also inflight, in order to meet the operational needs of the airline[15]. While the airline aims to minimize their operational costs for the entire fleet, the flexible allocation of a CI range for a flight ensures compatibility with legacy FMSs. Current FMS are operating with the CI, instead of defining the minimum and maximum direct operating costs of the flight directly.

$$s_{max,CI} = d_{TCP_n} - \int_{t_{current}}^{t_{TCP_{n,min}}} \left(\vec{V}_{cr,CI_{min}}(t) + \vec{V}_{wind}(t)\right) dt \tag{3.3a}$$

$$s_{min,CI} = d_{TCP_m} - \int_{t_{current}}^{t_{TCP_{m,max}}} \left(\vec{V}_{cr,CI_{max}}(t) + \vec{V}_{wind}(t)\right) dt \tag{3.3b}$$

Similar to the minimum and maximum PACeR lengths for the envelope limits, the economic PACeR limiting distances are calculated through an integration of the speed over time as is shown in Equation 3.3. The speeds $V_{cr,CI_{min}}$ and $V_{cr,CI_{max}}$ resulting from a CI can be calculated through the ECON Cruise Cost Function (ECCF)[16]. The economic PACeR is a subset of the envelope PACeR as formulated in Equation 3.4.

$$PACER_{economic} \subseteq PACER_{envelope} \tag{3.4a}$$

$$\text{with: } PACER_{economic} := \left\{x \in \mathbb{R}_+ | s_{min,CI} \leq x \leq s_{max,CI}\right\} \tag{3.4b}$$

$$\text{and: } PACER_{envelope} := \left\{x \in \mathbb{R}_+ | s_{min,envelope} \leq x \leq s_{max,envelope}\right\} \tag{3.4c}$$

The difference between $s_{max,envelope}$ and $s_{max,CI}$ is, in most cases, larger than the difference between $s_{min,envelope}$ and $s_{min,CI}$. This results as $V_{cr,min}$ and is always below $V_{cr,MRC} = V_{cr,CI=0}$ [17] and, depending on the chosen CI range, $V_{cr,max}$ can equal the speed for the maximum CI $V_{max,CI=MAX}$.

3.4.3 Trajectory renegotiation

The objective of the PACeR is to provide the pilot information on the current aircraft performance relative to the planned trajectory. The two performance indications from

[15] The RTA algorithm described by DeJonge [DeJ92] also relies on a CI range as input for the guidance calculation.

[16] See Appendix B.3 for details on the Minimum Cost Speed (ECON) calculation.

[17] Unless a negative CI is applied; this however, does not reflect the purpose of the CI to identify a cost efficient speed.

the PACeR (flight envelope and economic) allow the definition of an onboard process to follow, whenever the active trajectory is no longer achievable for the aircraft. The trajectory renegotiation may also be triggered from the AOC or ATC, or the pilot, at any time for other reasons.

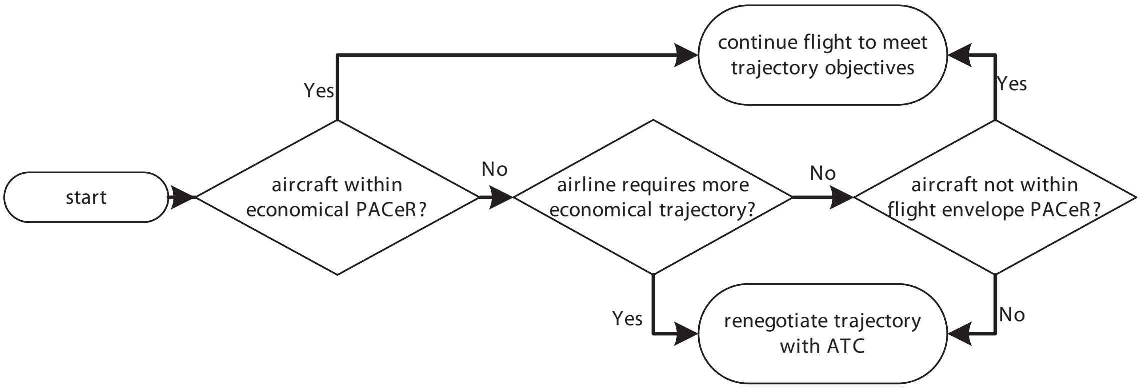


Figure 3.5.: Decision-making process to renegotiate aircraft trajectory

The process illustrated Figure 3.5 aims on aiding the pilot in decision making when a renegotiation of the trajectory is required. The process is initiated when the aircraft position is located outside the area along the trajectory enclosed by the economic PACeR. In this case, the pilot contacts the AOC, either via voice or data link communication, to receive permission to continue the flight on the planned trajectory contracted with ATC (even though it does not meet the airline's economic preferences) or to request new instructions. On the ground, the decision on how to proceed is made in coordination with ATC. Depending on the individual flight, the decision might differ. One example, where the AOC would decide to continue with the contracted trajectory (although not economic from a fuel perspective), is if many passengers would miss connecting flights causing the resulting costs to surpass the increased costs of fuel. If however, a more efficient trajectory can be found in coordination with ATC, this would ensure a timely arrival, the revision of the contracted trajectory would be initiated by the AOC. However, the on-ground process and considered variables are outside the scope of this thesis and these two examples shall only serve as illustrations of the AOC decision process[18]. If the aircraft's position is outside of the area enclosed by the flight envelope PACeR, a direct trajectory renegotiation of the trajectory with ATC is required. In this case, the trajectory objective can no longer be achieved by the aircraft endangering merging, spacing, separation, or flow optimization objectives of the ATM system.

[18] Vaaben [Vaa12] analyzed airline disruption management of today's operation, taking flight planning and fuel consideration into account, that could be expanded for use in TBO.

3.5 Trajectory guidance

Aircraft guidance is essential to adherence to a 4D trajectory. This thesis defines four trajectory guidance concepts[19] that can be categorized into three integration levels[20] using different integrations into aircraft control loops. The human integrates differently into these concepts, from taking over the manual guidance role, to only a monitoring and supervising role in the automatic integration. In all concepts, the pilot must still perform the trajectory negotiation and monitoring tasks, in addition to the trajectory guidance and is always the responsible entity for the safe execution of the flight. The following Section describes the proposed guidance concepts in more detail.

3.5.1 Manual control

A manual control integration can be applied wherever guidance of the aircraft should be independent of the aircraft systems. This is the case, when current autopilot modes or certification do not permit the planned application. For manual operations, the pilot has full control over the aircraft movement and receives guidance cues to meet the planned trajectory. Figure 3.6 illustrates the integration into the aircraft control loops similar to

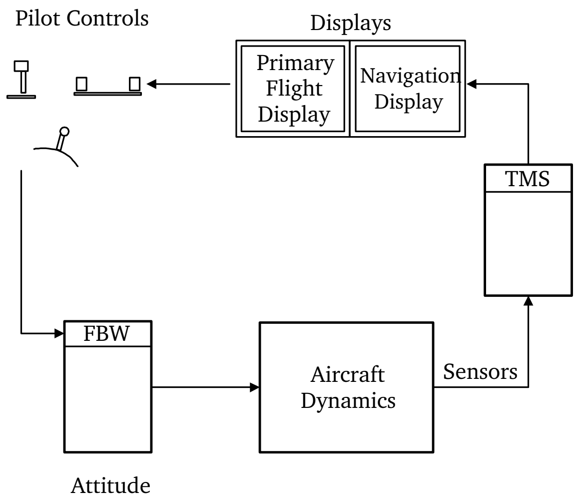


Figure 3.6.: Manual control loop

the Moires and Seabridges[21] [MS08] description of the aircraft attitude, trajectory, and flight mission control loops. The TMS takes the aircraft state information and planned trajectory into account to calculate guidance cues which are displayed to the pilot on the Primary Flight Display (PFD) in form of a flight director and speed advisories. The pilot uses the controls for the primary and secondary actuators (i.e. side-stick/yoke, throttle

[19] Manual-, time-, arrival- and automatic-control.
[20] Manual, semi-automatic and automatic.
[21] Compare Figure 2.13 in Section 2.4.

lever, and controls for speed brakes and flaps/slats) to follow the presented advisories. Note, that neither the Autopilot Flight Director System (AFDS) nor the FMS of the aircraft are used in the guidance for this concept.

A fully manually flown commercial flight is not realizable in operations today, because of passenger comfort, efficiency, safety, and pilot workload issues. As this thesis focuses on an operational integration of a retrofit TMS into today's commercial aircraft, the focus is not on a manual control integration. This integration can only be seen as a support solution to emulate future more advanced developments.

3.5.2 Time control

From the manual control concept, where the pilot performs the complete trajectory control task, with no assistance from automation, a first step towards an integrated TMS is to have the aircraft automation systems perform the tasks as on today's flight while the pilot performs the added task of time control along the trajectory. Figure 3.7 illustrates how such a system can be integrated into the aircraft control loops. The 3D navigation is performed by the aircraft's FMS and the task of time/speed control is performed by the pilot. This reduces the workload of the pilot for the guidance, compared to a manual control integration, as only one dimension needs to be controlled. The TMS is integrated as guidance loop around the AFDS with guidance cues from the TMS presented on the EFB.

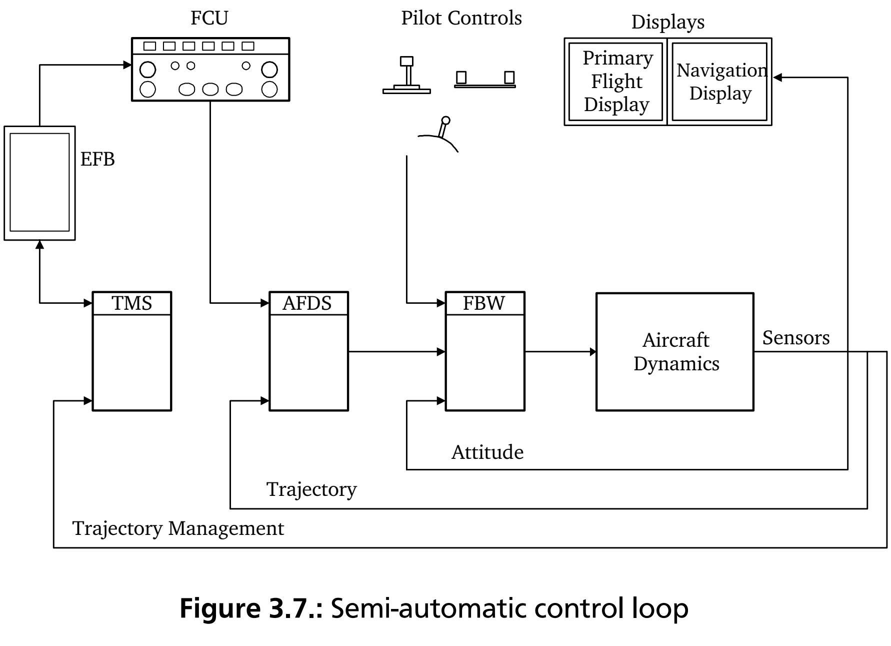


Figure 3.7.: Semi-automatic control loop

To provide the pilot with guidance information to make decisions needed to meet the temporal constraints of the trajectory, a controller needs to be designed that presents advisories as Calibrated Airspeed (CAS) or Mach number for the aircraft to fly. The guidance then needs to be discretized to allow an HITL integration, where the pilot transfers the cues presented on the EFB to the aircraft Flight Control Unit (FCU)/Mode Control Panel (MCP) for execution. The objective of this implementation is to provide guidance with only basic aircraft state information and a previously loaded planned trajectory of the aircraft. An EFB class 1 device with no connectivity to the aircraft avionics, but with an internal Global Navigation Satellite System (GNSS) sensor and loaded trajectory would be sufficient to fulfill the task. A dead band to limit throttle activity[22] is not needed in this integration, as the discretization of speed cues for the pilot already provides an adjustable dead band. The pilot sees the new speed cues only once the threshold of the discretization has been reached.

The control design follows a simplistic approach[23]. The pilot and aircraft performance was estimated as proportional elements with no dead time. Because of the strategic application of the guidance, a fast line-up is not required. This allows the assumption for the pilot and aircraft performance[24]. Figure 3.8 illustrates the control loop providing speed guidance to the aircraft, needed to meet a time constraint.

Inputs to the control framework include the difference in distance of the constraint TCP to the current aircraft position along the planned trajectory, and the difference between the RTA time of the constrained TCP and the current time. The average GS to meet the time constraint is calculated using these inputs. Under the made assumptions, the average GS can be equalized to the control GS, as is shown in Equation 3.5a. The pilot cannot enter a GS into the aircraft FCU/MCP, but a CAS or Mach number is required as input depending on the altitude at which the aircraft is flying. At given atmospheric conditions, the CAS_{ctrl} and M_{ctrl} can be computed using the BADA model [Eur12b] as illustrated in Equations 3.5b and 3.5c, with $\mu = \frac{\kappa-1}{\kappa}$ with $\kappa = 1.4$ and $p_0 = 101325$ Pa, $\rho_0 = 1.225\ \frac{\text{kg}}{\text{m}^3}$. The pressure p and Outside Air Temperature (OAT) T can be measured from aircraft sensors, allowing a calculation of the air density ρ at given humidity.

$$GS_{ctrl} = \frac{\Delta s}{\Delta t} = \frac{d_{TCP} - s}{t_{constraint} - t_{current}} \tag{3.5a}$$

$$CAS_{ctrl} = \left(\frac{2}{\mu} \frac{p_0}{\rho_0} \left\{ \left(1 + \frac{p}{p_0} \left[\left(1 + \frac{\mu}{2} \frac{\rho}{p} \left(GS_{ctrl} - V_{wind} \right)^2 \right) \right] \right) \right\} \right)^{\frac{1}{2}} \tag{3.5b}$$

$$M_{ctrl} = \frac{GS_{ctrl} - V_{wind}}{\sqrt{\kappa R T}} \tag{3.5c}$$

To fulfill the requirement of an integration into a non-connected EFB class 1, no access to these sensors can be realized. The only available sensor in the EFB is the GNSS receiver,

22 Compare Section 2.4.2 on FMS 4D control.

23 More advanced and cost efficient speed guidance methods have already been explored [DeJ92, RJO03, BCC13, DWDB12, GK95, MRW12, JPPS13]. Therefore, the focus of this thesis is on the HITL integration not the control itself.

24 Jardin [Jar97] described a more complex model of the aircraft and pilot behavior to generate speed commands that the Air Traffic Control Officer (ATCO) should communicate to the pilot to perform a 4D trajectory with no onboard capability.

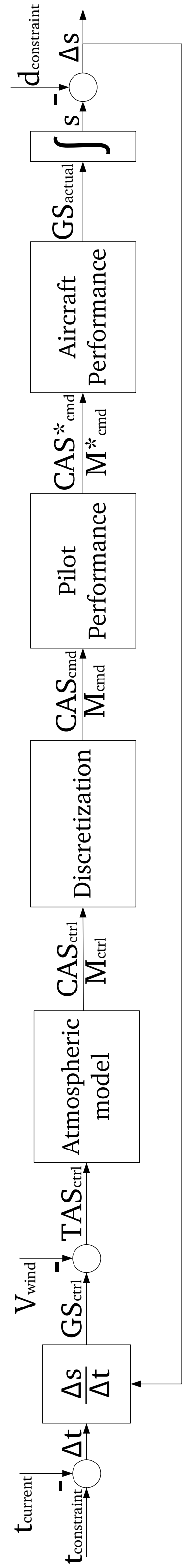


Figure 3.8.: Time control loop

which does not provide an altitude accurate enough to be used to calculate the static air pressure [WB11]. The increased predictability of TBO communicated through the ARINC 633 OFP [Aer12b] provides enough detail to estimate values for static air pressure and OAT. Predictions for the OAT are given in the OFP for each segment. Aircraft fly along FL[25], enables a direct conversion between the flown FL and the corresponding pressure p.

The calculated control variables ($\vec{CAS}_{ctrl}/\vec{M}_{ctrl}$) are discretized to limit the workload of the pilot and to serve as low-pass filter to limit throttle activity. The system displays only new CAS_{cmd} or M_{cmd} cues to the pilot when the calculated ETA[26] is outside the RTA window of the constrained TCP. In addition, a threshold has to be exceeded before updating the command variable.

The resulting values for CAS_{cmd} or M_{cmd} are presented to the pilot on the EFB. Ideally, the pilot transfers the displayed cues with no delay into the FCU/MCP. As deviation or false entries may occur, the commanded values to the aircraft are referenced as: CAS^*_{cmd} or M^*_{cmd}. From the provided command input and given environmental conditions, the actual ground speed GS_{actual} results depending on aircraft performance. Through an integration of GS_{actual} over time, a new distance to the constrained TCP can be calculated and fed back into the control loop.

3.5.3 Arrival control

Current arrival operations are inefficient, as they use stepped approaches to manage the separation and spacing of arriving aircraft, where Continuous Descent Approach (CDA) operations would be more economical (fuel savings) and ecological (reduced emissions and noise levels) [CBE+06]. The application of a continuous trajectory description is most beneficial for arrival operations, as the phase is relatively short (30-45 minutes), therefore limiting the effects of uncertainty in the weather modelling, and a high precision following of the trajectory ensures spacing and separation from other aircraft, especially in high density TCAs.

Therefore, the Continuous Descent Approach for Maximum Predictability (CDA-MP) guidance principle, which enables highly predictable CDA operations based on a continuous 4D trajectory, was chosen as the arrival guidance system for this thesis [LNF07, GLDL09, DGLL10, GLL11]. The concept was developed by Boeing Research and Technology Europe (BRTE) and adapted for the use in this thesis for a HITL integration, presenting guidance cues on an EFB similar to the time control in Figure 3.7. The control was expanded to take secondary control surfaces into account, to reduce the total energy error to the planned trajectory of the aircraft.

[25] This is above the transition altitude, which corresponds to a pressure altitude [Wal13].

[26] The ETA is calculated by dividing the remaining distance to the constraint TCP by the current GS of the aircraft and adding the current time.

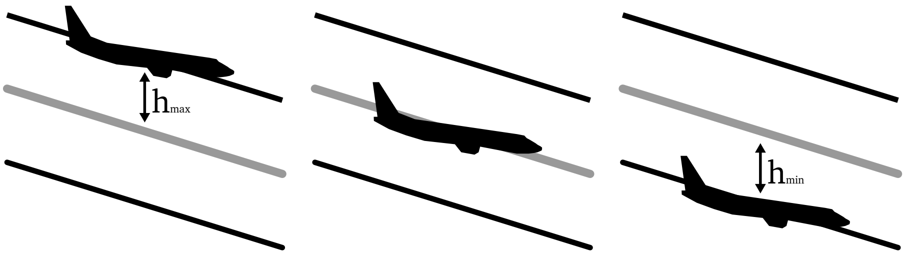


Figure 3.9.: Vertical CDA-MP modes

The guidance consists of speed and altitude guidance and the lateral route is followed using the standard FMS Lateral Navigation (LNAV) function. The speed guidance is calculated using a proportional controller with four gain parameters, resulting in changes to the CAS depending on GS-, change in GS-, time- and altitude-deviations [GLL11]. The vertical control is performed with three modes, depicted in Figure 3.9, where a dead band of allowed altitude deviations determines the application of each mode:

- **Nominal descent:** In case the altitude of the aircraft is within the allowed deviations to the planned trajectory altitude, as illustrated in Figure 3.9(b), the descent is flown in idle using the Vertical Navigation (VNAV) speed autopilot mode with autothrottle armed. Speed cues are presented to the pilot to reduce the time deviation from the planned trajectory.

- **Positive vertical deviation:** If the aircraft deviates from the planned altitude as illustrated in Figure 3.9(a), above the allowed deviation of the planned trajectory, an extension of the speed brakes is demanded by the guidance. The additional drag will reduce the vertical deviation, as the speed is kept constant through the flight level change autopilot mode with speed on elevator control. The mode is returned to nominal descent once the altitude deviation reaches zero.

- **Negative vertical deviation:** The control mode for negative vertical deviations, illustrated in Figure 3.9(c), was integrated differing from previous publications [LNF07, GLDL09, DGLL10, GLL11, Wes10] where a higher thrust was demanded by the system through an above idle engine N1. It was found, that the manual selection of an engine N1 was a task difficult for the pilot to accomplish [Wes10]. Therefore, the guidance was adapted, to now demand a vertical speed that is below the planned vertical speed of the trajectory. The aircraft regains altitude relative to the planned trajectory. Once the planned altitude has been regained, the optimal descent mode is demanded asking for the level change autopilot mode and idle thrust [WKS12].

The guidance is expanded to modify the point in time when the flaps are extracted, from the planned time defined in the continuous trajectory, during the descent in order to minimize the total energy error of the aircraft [Wes10, WZ12]. The application can only assist in reducing the total energy error shortly before the final approach; however, in this case the vertical dead band is reduced to a minimum and deviations to the planned trajectory should be minimized. The time difference Δt to the nominal planned time of flaps extension is calculated with Equation 3.6[27].

$$\Delta t = \frac{2 \cdot \Delta h \cdot m \cdot g}{\rho \cdot V^3 \cdot S \cdot \Delta C_D} \tag{3.6a}$$

$$\text{with: } \Delta h = \left(h_{current} - h_{planned}\right) + \frac{1}{2g} \cdot \left(\vec{V}^2_{current} - \vec{V}^2_{planned}\right) \tag{3.6b}$$

Where ΔC_D is the difference in drag coefficient before and after the flaps extension and Δh is the energy error equivalent altitude.

3.5.4 Automatic control

The computer surpasses the human among others in regards of computation, replication and speed[28]. This makes the automation of a monotonous task as the control of the adherence to a 4D trajectory ideal. However, as identified, the pilot needs to always be aware of how the automation is functioning for a complete mental picture of the situation, as well as being able to take over the task of the automation in case the system fails. Therefore, the pilot needs a detailed understanding of the trajectory and its objectives, the automation is following.

For an automatic control integration as retrofit for today's aircraft, the 4D guidance is integrated as additional function into the aircraft FMS. The TMS integrated as outer control loop, as illustrated in Figure 3.10, only fulfills the functions of trajectory negotiation and monitoring.

In this integration the EFB serves as platform, to negotiate the trajectory with the AOC and monitor the cost efficiency of the trajectory. An agreed trajectory is send to the FMS either through a direct onboard connection, or using ACARS data link from the AOC, for execution. During the flight execution, the pilot monitors the economic PACeR on the EFB, to ensure efficient 4D operations. The FMS is guiding the aircraft along the planned 4D trajectory taking all constraints into account. An onboard monitoring and alerting[29] is required to alert the flight deck crew when the aircraft flight envelope does not permit the fulfilment of all trajectory objectives.

An integration into service requires a software and/or interface update to the FMS. Many aircraft today are capable of fulfilling a single RTA[30]. To enable full 4D opera-

[27] See Westphal [Wes10] for a derivation.
[28] Compare to Section A.1 on function allocation and Section A.1.2 on automation.
[29] Comparable to the onboard monitoring and alerting of the lateral RNP navigation [Int08].
[30] Compare to Section 2.4.

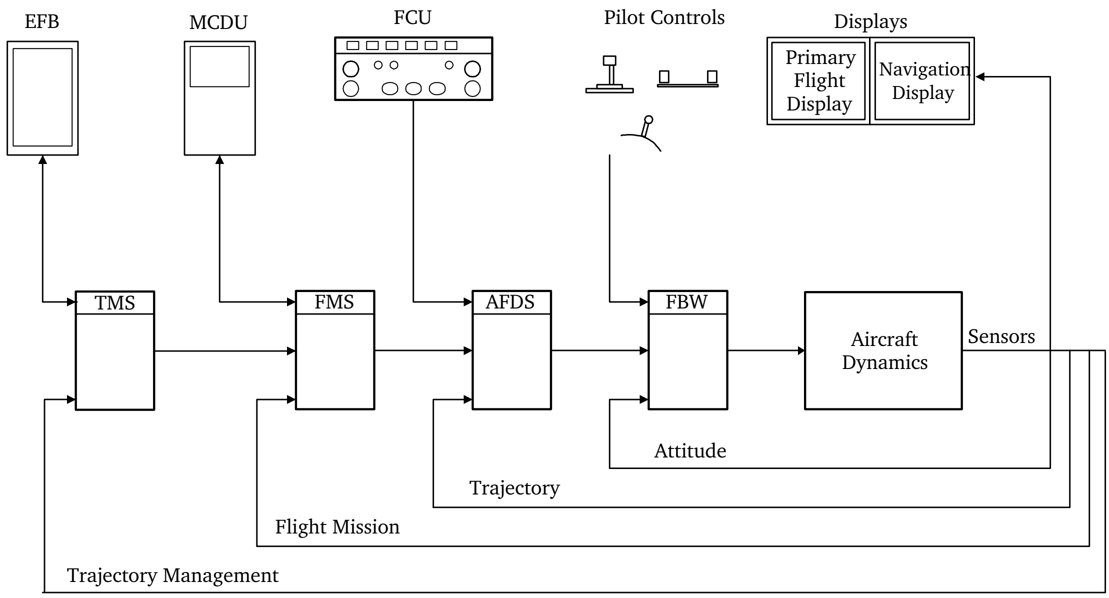


Figure 3.10.: Automatic control loop

tions with this integration, a software update to the FMS is required to support multiple time constraints, or trajectory updates, which are send to the FMS from the EFB or via ACARS data link. To enable a direct connectivity between the EFB and FMS, the hardware/software interface must allow the transfer of proposed trajectories in both directions[31]. In addition, the FMS software must support both onboard monitoring and alerting of the time adherence function. As the interface of the FMS is limited to mostly text information on the MCDU/CDU, the EFB is needed to brief complex trajectories, to strategically negotiate trajectories with the AOC, and to monitor the economic fulfillment of the temporal trajectory objectives.

[31] One means of integration is the use of the Communication Management Unit (CMU) [Aer10a], exchange flight plan messages between EFB and FMS.

4 Realization of an onboard retrofit trajectory management system

System architecture and software integration are especially important for an onboard retrofit Trajectory Management System (TMS). An integration into an Electronic Flight Bag (EFB) was determined to be the best use of resources[1], defining the hardware platform for the implementation. The focus of the system architecture is on the interface definition: How can the EFB solution communicate with onboard avionics and ground systems? The prototypical software is implemented into an existing solution that is expanded for the three defined functionalities of an onboard retrofit TMS[2]: negotiation, monitoring, and guidance.

4.1 Architecture

The architecture of an onboard retrofit TMS should be designed modularly and should be feature independent to allow different integration levels and minimize errors. The objective of the architecture is to enable interfaces between the TMS and the following three systems: the Flight Management System (FMS), the Airline Operations Center (AOC), and the Air Traffic Control (ATC). Systems are integrated with the TMS as the centerpiece of the architecture, running on EFB hardware aboard the aircraft.

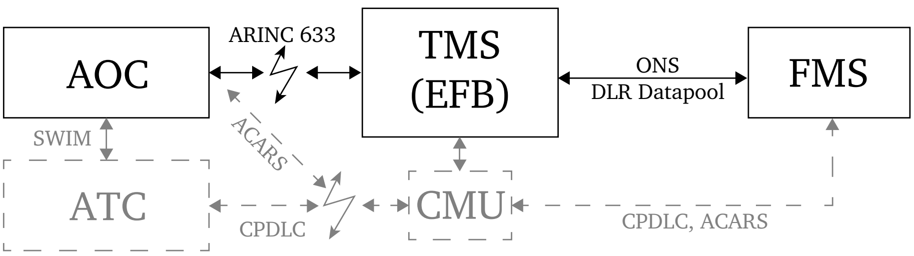


Figure 4.1.: Simplified interfaces of a retrofit onboard trajectory management system

Figure 4.1 illustrates these systems and interfaces[3]. Shown in black are the realized systems and interfaces for the purpose of this research. Shown in grey are additional interfaces and systems needed for a fully functional onboard TMS. The AOC is connected

[1] Compare to Chapter 1.
[2] Compare to Chapter 3.
[3] More detailed descriptions of the architectures for each experimental carrier can be found in Appendix E.

with the TMS over data link using Aeronautical Radio Incorporated (ARINC) 633 Electronic Flight Folder (EFF) [Aer12b] data exchange. Messages can be retrieved from FMS via the Onboard Network System (ONS) or the Deutsches Zentrum für Luft- und Raumfahrt e.V. (DLR) datapool and in case of the DLR datapool also send to the FMS from the TMS. The realized integration does not cover the integration with ATC, additional systems and interfaces would be needed to support this functionality. One example would be the integration with ATC via Future Air Navigation System (FANS) 2/B Controller-Pilot Data Link Communications (CPDLC) [Hon13]. Also currently used Aircraft Communications Addressing and Reporting System (ACARS) messages [Aer12c] for AOC communication could be used with a Communication Management Unit (CMU) [Aer10a] onboard the aircraft. In any case the final decision to implement changes to the trajectory is performed in certified hardware on the FMS. The following sections detail the connectivity between the systems and the hardware integrations.

4.1.1 AOC connectivity

The used EFB application from Jeppesen included the TMS and provided an AOC data link connection over a Jeppesen proprietary communication infrastructure exchanging ARINC 633 [Aer12b] messages. This interface allowed the communication of flight plans, reroutings and transient information, such as Notice to Airmen (NOTAM) and Weather (Wx) data, before and during the flight, using a Secure Sockets Layer (SSL)-Virtual Private Network (VPN) connection to the AOC in Gdansk, Poland.

The existing connectivity was expanded to allow the communication of full 4D and continuous trajectory descriptions. A trajectory exchange model was developed[4] that allows the definition of constraints at Trajectory Change Points (TCPs). In addition, a continuous trajectory definition can be integrated into the exchange model as a string field describing the aircraft state vector at given timestamps. Linear interpolation determines the aircraft state vector between two timestamps, assuming a high sampling rate of the data[5].

4.1.2 ATC connectivity

No ATC data link connectivity was integrated for the purpose of this thesis. However, an ATC coordinated flight plan, including time constraints, was received, briefed, and negotiated aboard the aircraft. The TMS would serve as additional display to create or display of CPDLC messages. Certified interfaces, such as the Data link Control and Display

[4] See Figure C.1 in Appendix C.1.

[5] The exchange of a continuous trajectory description was used for the Continuous Descent Approach for Maximum Predictability (CDA-MP) arrival guidance integration. See Figure E.3 in the Appendix for details on the implemented architecture of the message exchange between the airborne and ground systems. In this integration the ground system provided the aircraft state vector at 0.3 to 0.2 Hertz.

Unit (DCDU) or Control Display Unit (CDU), can send messages or implement actions pertaining to the aircraft avionics via the aircraft CMU. These messages would be exchanged for tactical changes to the trajectory. The TMS focuses on strategic trajectory negotiations coordinated with the AOC[6]. These strategic trajectory negotiations can be performed in collaboration with the AOC. In this case the AOCuploads the agreed trajectory update via ARINC 633 [Aer12b] or ACARS [Aer12c]. Therefore no CPDLC functionality was integrated or tested within the scope of this research.

4.1.3 FMS connectivity

Either no access, write access, read-only access, or read/write access was permitted to the FMS, depending on the application. The purpose of the simulator trials was to demonstrate enroute 4D guidance with an EFB class 1, which focused on easy integration into the flight deck, without permitting FMS integration[7]. Read-only connectivity to the FMS was realized for the ecoDemonstrator flight trials using the Boeing ONS to which the TMS interfaced via a Wireless local area network based on IEEE 802.11 standards (WiFi) using the JavaScript Object Notation (JSON) data format. Additional information, such as a continuous trajectory description that the pilot followed with the assistance of guidance cues, was communicated from the AOC[8]. In the Heterogeneous complex air traffic (HETEREX)[9] flight trials, the focus was on a tight FMS integration[10], where the trajectory was uploaded as constraint list from the TMS to the FMS, to calculate a flyable trajectory to follow. This trajectory was sent back to the TMS for display and application of the monitoring functionality[11].

4.1.4 Hardware integration

For the purpose of this thesis, the TMS was integrated into four different hardware platforms. Two of these integrations were certified as class 2 EFBs and two were commercially available tablet computers principally designed for the consumer market. Both qualified as EFB class 1 devices, with the Apple iPad receiving operational approval [Fed11b]. In all cases, the hardware was driven by a Windows XP or Windows 7 operating system, either directly on the device or streamed in case of the iPad using the application iDisplay [sha13]. While all hardware was sufficient to run the application, the computation

[6] Compare to Section 3.3.
[7] Compare to Chapter 5.
[8] Compare to Appendix E.1.2.
[9] The HETEREX project was funded by the german Federal Ministry for Economic Affairs and Energy through the Luftfahrtforschungsprogramm (LuFo) programm.
[10] Compare to Section 6.2.
[11] See Figure E.10 in Appendix E for an overview of the architecture integrated for the HETEREX test flight, and Figure E.6 for the previous integration into the DLR Generic Experimental Cockpit Simulator (GECO) simulator for an *a priori* evaluation.

performance increased significantly with the use of Solid-State-Drives (SSDs) and higher processing speeds. The purpose of the various hardware integrations was to demonstrate the independence of the overall operational concept from hardware specifications and integrations. In addition, it highlighted those functionalities demanding a tighter integration, and therefore, requiring an EFB class 2 system[12]. The EFB hardware systems are namely:

Apple iPad 2 - The iPad served as external touchscreen of an Hewlett Packard (HP) server for the BOEING ecoDemonstrator test flight and previous simulator sessions[13].

Samsung slate series 7 - The slate demonstrates the possibility to run the software, in which the TMS was integrated, natively, on a Commercial off-the-shelf (COTS) tablet device. This tablet was used for demonstrations and in the simulator campaign in the TECHNISCHE UNIVERSITÄT DARMSTADT (TUD) simulator[14].

NavAero EFB - The TMS was integrated on the t·Bag C^2 into the DLR GECO and featured an ethernet and an ARINC 429 [Aer12a] connection, and differed from the COTS devices, by using the NAVAERO t·Pad 2000 resistive touch screen[15].

Rockwell Collins A320 EFB - During the HETEREX test flight in the DLR Advanced Technology Research Aircraft (ATRA), the onboard EFB driven by a Fujitsu Lifebook P771 laptop hosted the TMS. This was a similar integration to the NAVAERO t·Pad but had higher processing power used in the Rockwell Collins EFB and a resistive touchscreen fixed in landscape orientation[16].

The data link for the flight trials was a commercial SwiftBroadband satellite connection for the ecoDemonstrator flight, and a DLR proprietary data link using a directional antenna, located at the DLR facility in Braunschweig-Wolfsburg, Germany, ICAO-Code (EDVE), for the HETEREX flight. In both cases, the JEPPESEN communication infrastructure communicated the ARINC 633 [Aer12b], and trajectory messages to and from the AOC via an SSL-VPN connection to the AOC in Gdansk, Poland. The data link hardware platforms were exemplary only, used to show the potential to communicate trajectory data using satellite or terrestrial data links between the AOC and the aircraft.

4.2 Software demonstrator

The concept of the TMS was integrated into the JEPPESEN Gate-to-Gate (G2G) application. The software is an integrated, data-driven supplemental aeronautical information display.

[12] That is, the depiction of an ownship symbol inflight, or the integration with the FMS or CDU.
[13] See Section 6.1 and Appendix E.1 for details.
[14] See Chapter 5 for details on the integration during the simulator trials.
[15] See Appendix E.2.1 or GIESE and WESTPHAL [GW13] for details on the GECO simulator trials within HETEREX.
[16] See Section 6.2, Appendix E.2.2 or GIESE and WESTPHAL [GW13] for details on the integration into the ATRA.

It was developed before, and in parallel to, the execution of the research presented in this thesis, to serve as next generation Instrument Flight Rules (IFR) charting application [PSB+11, WSZ+11, PTEH12]. The chart is rendered from a database containing all navigational information. The rendering engine utilizes a theme file for the graphical depiction of information, which allows an adaptation of the chart graphics depending on the aircraft type on which it is used[17].

Figure 4.2 shows the available functions. A briefing package can be requested via data link from the AOC containing the flight plan (Figure 4.2(a)), NOTAM (Figure 4.2(b)), and Wx information. The information is filtered depending on the zoom level and phase of flight, integrated into one seamless data-driven chart. Depending on the flight phase and selected procedure, terminal procedure information is displayed (Figure 4.2(c)). In the taxi-phase, G2G does not only depict an Airport Moving Map (AMM) but provides taxi routing, either through inputting the taxi route as received from ATC (such as a D-TAXI CPDLC message [LBW+10]), or by calculating the shortest possible route (Figure 4.2(d)).

An integration into this framework had the advantage that the concept of the application already supported features not available on today's charting products, which were required for the TMS integration. A data driven chart is required to depict the negotiation of a trajectory for the entire flight with geo-referenced constraint labels.

4.3 Trajectory negotiation

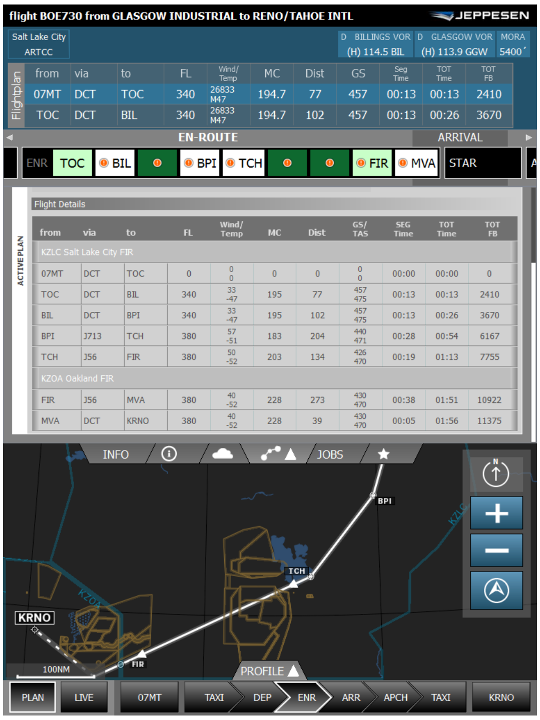
The negotiation of a trajectory can be divided into two phases. The first phase is the communication of the trajectory information between the involved stakeholders and the workflow of the pilot initiating or receiving a trajectory update. The second phase is to brief the pilot on the updated trajectory. This briefing leads to the final decision by the pilot as to whether to fly the revised trajectory.

4.3.1 Communication

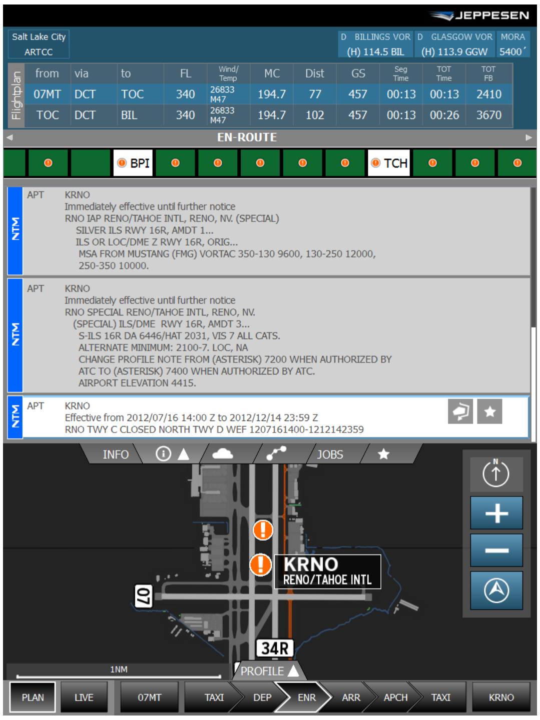
The trajectory negotiation can be initiated either by a stakeholder on the ground or by the pilot. From a pilot perspective, the negotiation depends on the use case[18]. In all cases, the final decision to send a trajectory from the TMS to another system is performed as an accept or decline decision within the centralized task management system of G2G [BSW12]. The communication with the AOC can be initiated by the pilot through three different mechanisms: a briefing package, an in-flight re-routing (optimization), or a CDA-MP trajectory. The briefing package and re-routing functions were implemented within G2G, independent of this thesis, as an ARINC 633 [Aer12b] flight plan. The re-

[17] Note: The depiction of the FMS route was for example changed depending on the flight trials from magenta for the ecoDemonstrator (Boeing 737) to green for the HETEREX trial (Airbus A320).

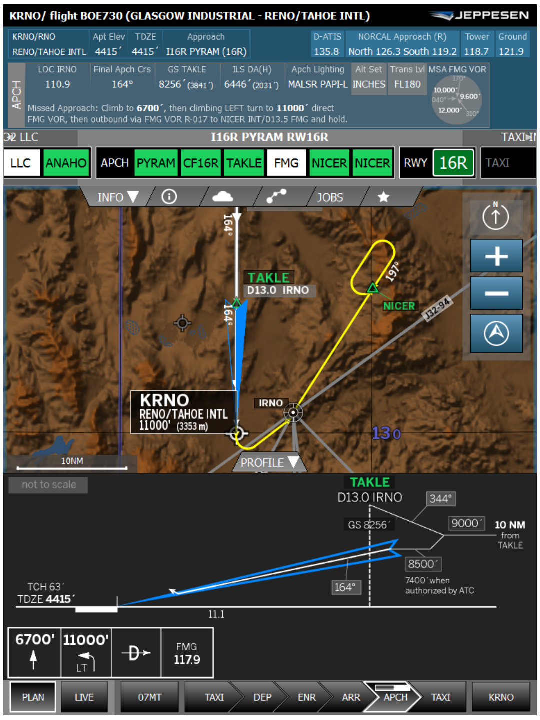
[18] See Section 4.5.2 for the definition of the request of a Continuous Descent Approach (CDA) and Section 4.5.4 for the communication to the aircraft FMS.



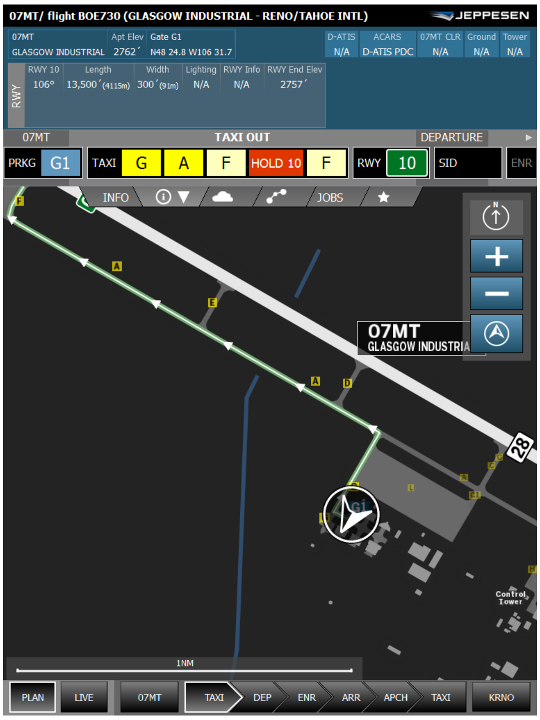
(a) Flight plan ©JEPPESEN



(b) Graphical NOTAMs ©JEPPESEN



(c) Approach chart ©JEPPESEN



(d) Taxi routing ©JEPPESEN

Figure 4.2.: JEPPESEN's Gate to Gate application

quest for these features is initiated with the "NEW JOB" function in the task management system of G2G as shown in Fig.4.3. The flight plan definition was expanded to allow the definition of full 4D trajectories including, terminal procedures, time, altitude, and speed constraints.

Figure 4.3.: Options to request a trajectory update from the AOC

Updates to the trajectory can be initiated by the stakeholders on the ground at any time. The pilot is notified of updates in G2G. The pilot can review the update, accept it or decline it, or propose alternatives. For communication with the AOC, this communication is performed directly within the TMS and the accepted trajectory can be sent to the FMS for execution. For the communication with ATC, the final accept or decline decisions are performed through certified avionics and only the proposal for an alternative can be created in the TMS. Changes to the active FMS route are reflected in G2G with no user interaction required, ensuring data coherence between the FMS and EFB.

The Constraint Editing System (CES) shown in Figure 4.4 has been integrated into the TMS, to provide the pilot the possibility to collaboratively define the constraints, as the expression of the users preferences, with the ATC and AOC. A touch-optimized interface is provided from the CES to alter constraints at given TCPs. The constraint mode and value can be altered using the CES touch buttons as illustrated in Figure 4.4 for the waypoint "KEROP".

The only requirement all realized systems had in common was a data link connectivity to the AOC. Otherwise, the communication methods could be adapted depending on the system integration level.

4.3.2 Briefing

The briefing focusses on a geo-referenced representation of the trajectory and its constraints. Therefore, the constraints were integrated into the rendering engine of G2G to show the entire trajectory. Figure 4.5 shows a time and altitude constraint at the waypoint "KEROP" for a full 4D trajectory. The depiction of the constraints was conceptualized in the author's diploma thesis [Wes10]. This example shows time constraints identical to altitude constraints as specified in International Civil Aviation Organization (ICAO) An-

Figure 4.4.: Constraint editing system

nex 4 [Int09][19]. The set constraints are an example of how time and altitude constraints can be used as an interface between two bordering Flight Information Regions (FIRs) helping to manage the traffic flow of sectors. While the geo-referenced representation of the constraints can assist the pilot to locate constraints and to inform about the numerical value, no information is included regarding the economy or feasibility of the trajectory. The assumption is that the trajectory was already checked for feasibility from the AOC; however, an onboard verification is required.

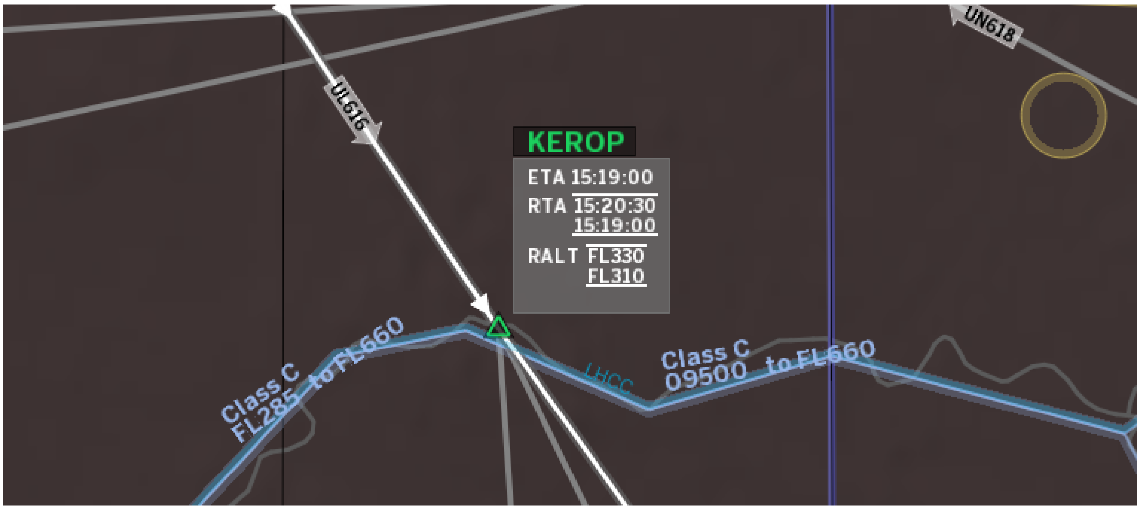


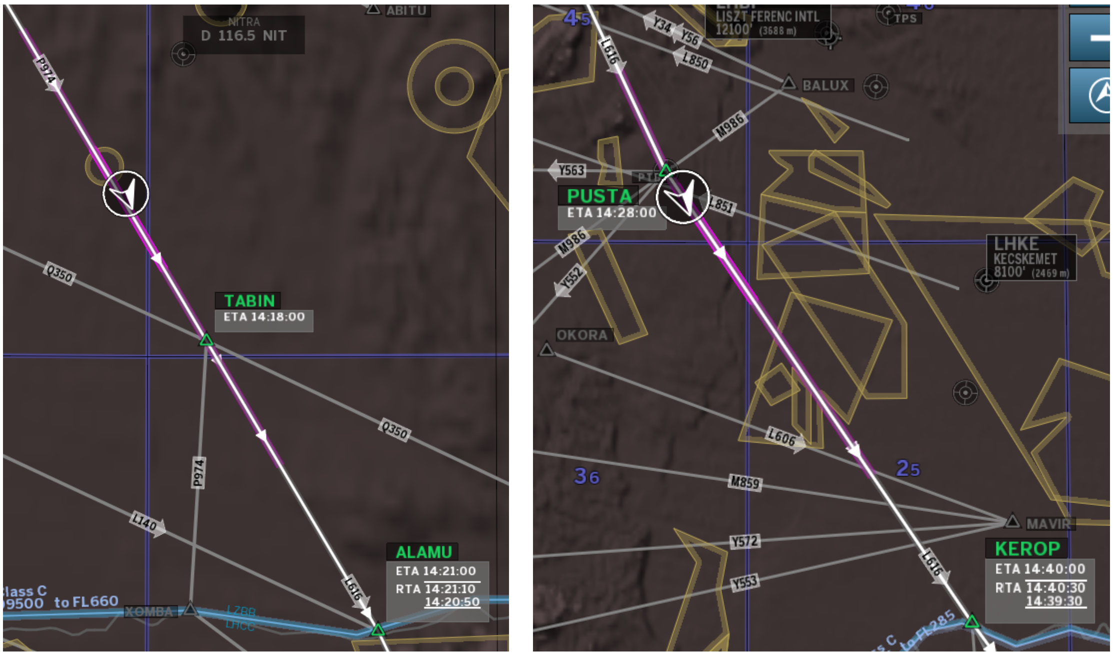
Figure 4.5.: Constraints at waypoint "KEROP"

The Precision Aircraft Control enhancing Route (PACeR) designed for the trajectory monitoring assists the pilot in judging whether or not a trajectory is feasible within economical and operational constraints.

[19] Compare to Table C.1 in Appendix C.3 for a detailed description on the constraint coding.

4.4 Trajectory monitoring

The PACeR was added to the Jeppesen G2G application to enable an eased trajectory monitoring for the pilot. The depiction becomes active once a trajectory with one or multiple time constraints is loaded.



(a) "ALAMU" constraint (b) "KEROP" constraint

Figure 4.6.: PACeR over time

Figure 4.6 illustrates the PACeR behavior over time. Two time constraints along the trajectory were defined to coordinate entering and leaving the Budapest, ICAO-Code (LHCC) FIR. Figure 4.6(a) illustrates the economical PACeR in magenta, and the envelope PACeR in opaque magenta, before reaching the constrained waypoint "ALAMU". After entering the LHCC FIR, the algorithm identifies "KEROP" as next constrained TCP shown in Figure 4.6(b). After leaving the LHCC FIR, no further constraints exist along the trajectory and the PACeR depiction becomes inactive, as the temporal monitoring of the trajectory is no longer required.

For the HETEREX trials, only the envelope PACeR was implemented. The system received the minimum and maximum achievable speeds from the DLR FMS. In the integration into the TUD simulator, both the envelope and economic PACeR depictions were integrated, calculating the achievable speeds with input from the simulator and the European Organisation for the Safety of Air Navigation (EUROCONTROL) Base of Aircraft Data (BADA) [Eur12b] performance model. In both integrations, the depiction of the PACeR was implemented in magenta, which is already used for the depiction of constraints in the AIRBUS color scheme[20].

4.5 Trajectory guidance

A Human Machine Interface (HMI) is required for the four trajectory guidance integrations proposed in Section 3.5. This interface must provide the pilot with either guidance information for which the following of the desired trajectory of the aircraft can be assured, or, in case of an automatic integration, a workflow needs to be implemented, to transfer the trajectory information from the TMS to the FMS for following the trajectory. The realized interfaces for all four integrations are presented in the next Sections.

4.5.1 Manual control

The manual control concept was not specifically implemented within this thesis. It is used by the DLR in flight trials with the A320 ATRA to follow guidance from the DLR research FMS. Either a flight director or a "birdy" is presented in a Primary Flight Display (PFD) to the pilot on a foldable display[21] as is shown in Figure 4.7.

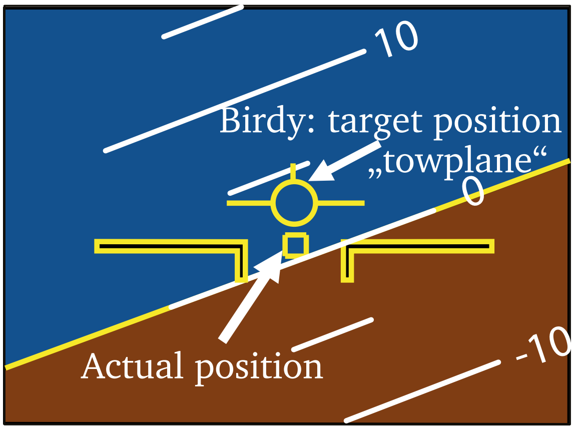


Figure 4.7.: DLR flight director after KUENZ ET AL. [KMK07]

This integration is a work-around, as currently certification does not allow a direct access from the DLR FMS to the aircraft's systems. This was the case on the previous DLR aircraft the Advanced Technologies Testing Aircraft System (ATTAS). The integration does not state a design option for an operational integration into a commercial airline flight deck as one pilot is fully occupied by monitoring and controlling the trajectory relative to the reference. The task of manual control can be performed by specially trained experimental pilots for test flights where it has proven sufficient accuracy [KMK07], but is

[20] For an integration on a BOEING aircraft the color would be modified to represent the BOEING color scheme.

[21] Compare with Figure 6.6(b) in Section 6.2.2.

binding too many resources and too exhausting to perform over the duration of a commercial flight.

4.5.2 Arrival control

The idea to implement an arrival guidance as Human-in-the-Loop (HITL) interface for the CDA-MP guidance principle was developed by Boeing Research and Technology Europe (BRTE). The HITL was first implemented by Boeing Research and Technology as cues in the PFD and Navigation Display (ND), and evaluated in a simulator study [Moo09]. A first integration to display guidance cues on an EFB was performed in the author's Diploma Thesis preceeding this work [Wes10]. Since then, the interface was re-iterated multiple times with feedback from simulator sessions with pilots, human factors experts, and designers[22]. Figure 4.8 illustrates the final design of the guidance bar presenting the guidance information for different guidance modes during the descent[23].

The guidance system was embedded into an operational concept for the trajectory request and communication with the AOC [WKS12]. The concept assumes that the system is used at an airport where one major operator is granted flexibility from ATC in the coordination of its arriving aircraft. It is the pilot's decision to initiate a request for a CDA[24]. The request is performed by selecting an approach procedure as CDA, where the procedure can either be assigned from ATC via voice communication or selected as a request from the pilot. The option to select a CDA procedure is shown in Figure 4.9(a), where CDA in parentheses indicates an available CDA-MP approach. After reviewing the procedure, the pilot can decide to downlink the request to the AOC, or to fly the procedure as conventional approach and cancel the request, as shown in Figure 4.9(b), as an option in the task management system of G2G [BSW12]. On the ground, a reference trajectory is calculated taking Wx predictions and other arriving aircraft into account. Required Time of Arrivals (RTAs) can be assigned, and will be considered in the continuous trajectory description. This allows effective management of the traffic situation, either manually by an operator or automatically through an algorithm. Once the trajectory is calculated, it is transmitted to the aircraft, where the pilot is notified in G2G (Figure 4.9(c)) and can activate the guidance bar and operational TCPs that are displayed on the chart[25].

[22] Compare to the spiral human-centered design process presented in Section A.1.2 and Appendix C.4 for the evolution of the guidance bar design.

[23] See Figure C.2(a) in Appendix C.2 to learn how the guidance bar is integrated into the G2G application and Section 3.5.3 for details on the guidance modes.

[24] As the flight deck crew might have reasons opposing the use of a 4D CDA such as crew fatigue, aircraft condition, etc.

[25] See Figure C.2(a) in the Appendix.

(a) cruise flight with countdown to top of descent

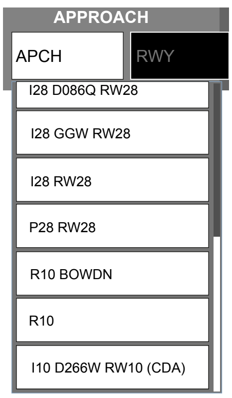
(b) nominal descent

(c) negative vertical deviation with vertical speed cue

(d) positive vertical deviation with speed brake cue

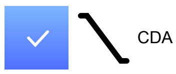
(e) nominal descent with changed speed and flaps cue

Figure 4.8.: CDA-MP guidance bar in different guidance modes



(a)

(b)



(c)

Figure 4.9.: CDA-MP trajectory negotiation workflow

4.5.3 Time control

The concept of time control is a variation of the arrival control concept for the enroute flight phase. It is assumed that aircraft fly at a constant altitude in cruise for most of the flight[26]. The overall concept in this thesis is to allow the integration of a TMS into as many aircraft as possible, for the Air Traffic Management (ATM) system to benefit from a high equipage rate[27]. The time control concept can be implemented into aircraft, without an RTA control capability in the FMS, by presenting speed guidance cues to the pilot. The integration shown in Figure 4.10 depicts a Mach or Calibrated Airspeed (CAS) cue for the pilot to enter in the Flight Control Unit (FCU)/Mode Control Panel (MCP) and additional information to the aircraft RTA and Estimate Time of Arrival (ETA) at the next constrained TCP. In addition the identifier of the next constrained TCP is given.

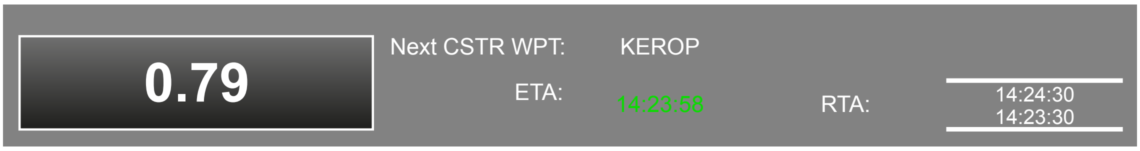


Figure 4.10.: Time guidance bar

The system requires only basic Global Navigation Satellite System (GNSS) and trajectory data and can calculate the speed guidance using the EUROCONTROL BADA atmospheric model [Eur12b]. Pilot response and aircraft are modeled as ideal control behavior, allowing the system to be applied to any aircraft type[28]. To minimize the change in speed, the speed or Mach cue is only updated when the ETA is outside the RTA boundaries and only if a deviation to the currently shown cue of more than a threshold limit is reached[29]. The speed or Mach cue is always set to meet the middle of a "**between**" time constraint[30]. If a deviation of the speed/Mach cue to the current speed/Mach larger than Mach 0.02 occurs, the speed/Mach cue is colored blue to attract pilot attention. The pilot then decides if this is a desired state, or if a speed change is required. The ETA is also color-coded. If the ETA is within the boundaries of the RTA, it is displayed in green. If a smaller deviation (up to half of the RTA constraint window) of the ETA to the RTA is present, the ETA is shown in orange. If a larger deviation of the ETA to the RTA occurs, it is displayed in red. Once a constraint TCP is passed, the guidance switches automatically to the next constrained TCP.

[26] Step climbs are performed as specified in the trajectory to optimize the fuel economy of the flight.

[27] Compare to Chapter 1.

[28] The minimum and maximum allowable speeds need to be modified depending on the aircraft type and environmental conditions.

[29] For the evaluation, the threshold was set to $CAS_{cmd} - 5kts < CAS_{ctrl} < CAS_{cmd} + 5kts$ or $M_{cmd} - 0.015 < M_{ctrl} < M_{cmd} + 0.015$. Compare to Section 3.5.2

[30] Variations might be beneficial for larger time constraint windows to minimize the speed changes to the next constraint; however, these were not considered in the scope of this thesis.

4.5.4 Automatic control

The automatic control concept was not implemented as a control system for this thesis, but was evaluated from a workflow perspective. For the HETEREX flight, an integration into an automatic control concept was combined with the manual execution of the control. This concept allows the management and briefing of the trajectory within the TMS, which then sends the trajectory - or parts of it - to the FMS for execution. For an integration with current FMS, only the part of the trajectory to the next time constrained TCP could be sent. Current FMS can comply only to one RTA after passing the constrained TCP an update is sent to the FMS including the trajectory to the next time constrained. This work-around can enable full 4D operations with the current FMSs. If software updates to the FMS would permit the handling of multiple time constraints on current avionics hardware, the TMS offers a possible advantage of a graphical briefing and monitoring of the trajectory.

Figure 4.11.: FMC connectivity

The pilot can send a trajectory to the FMS after reviewing it (for example selecting a terminal procedure to be flown) and through the centralized task management system of G2G [BSW12], selecting the "send to FMS" function shown in Figure 4.3. After the selection, the pilot can review the trajectory before confirming and sending the trajectory (Figure 4.11). This enables the constraint editing mode to create or change constraints at TCP[31]. In the HETEREX integration, the uplinked trajectory appears as an ATC uplink in the FMS, where a flyable trajectory can be calculated from the given constraints and followed by guidance. The active trajectory is then uploaded to the EFB to be displayed in the TMS.

31 With the CES depicted in Figure 4.4.

5 Evaluation in a research flight simulator

The realized concept needed to be evaluated to determine the usability for pilots to negotiate and monitor a trajectory, guide the aircraft along it and prove the operational feasibility of the realized guidance system. For this, simulator trials were organized and are discussed in the following Sections. First, the concept is described. Next is an overview of the trial execution and the analysis of the collected data succeeding the trials followed by a summary of the findings.

5.1 Concept

The concept of the simulator trials is described in the following Section, which lists the scope of the trials, followed by a description of the systems integrated in the TECHNISCHE UNIVERSITÄT DARMSTADT (TUD) research simulator. The operational scenario describes how the Gate-to-Gate (G2G) system and full 4D trajectories were applied. To evaluate the objectives set in the scope of the trials, hypotheses were formulated, measurements selected and are discussed.

5.1.1 Scope

The research simulator trials helped to evaluate the usability, Situation Awareness (SA), demand, and performance using a Trajectory Management System (TMS) on a low-integrated class 1 Electronic Flight Bag (EFB). The purpose of the research was to answer the question "Can an EFB-based TMS support the pilot in executing the tasks of trajectory negotiation, monitoring, and guidance in a full 4D trajectory environment?". A low integration of the EFB with the aircraft systems was chosen to enable easy and cost-efficient integration into the aircraft flight deck, requiring only a data link connection to the Airline Operations Center (AOC) and basic aircraft state information (such as Global Navigation Satellite System (GNSS) data).

The briefing of a trajectory with G2G is compared to a briefing using current avionics to determine if the pilot is aware of all imposed constraints, the provided system is usable, and that this provides a better means for briefing a trajectory than the aircraft Flight Management System (FMS).

For the evaluation of the Precision Aircraft Control enhancing Route (PACeR) monitoring feature it is necessary to know that the pilot is aware of all imposed temporal constraints, if the depiction increases pilot's temporal awareness of those constraints compared to current means, and whether or not the system is usable.

The time guidance function is evaluated to determine the feasibility for aircraft without an Required Time of Arrival (RTA) functionality to meet enroute time constraints. The time guidance function also evaluates the general feasibility the pilot's demands during the task execution and the usability of the system.

5.1.2 Simulation environment

The TUD research flight simulator was used for this study. It was adapted from previous studies to allow an integration of the developed system into an A320 type flight deck[1]. These previous studies focused on manual flight or taxiing, where direct pilot input to the

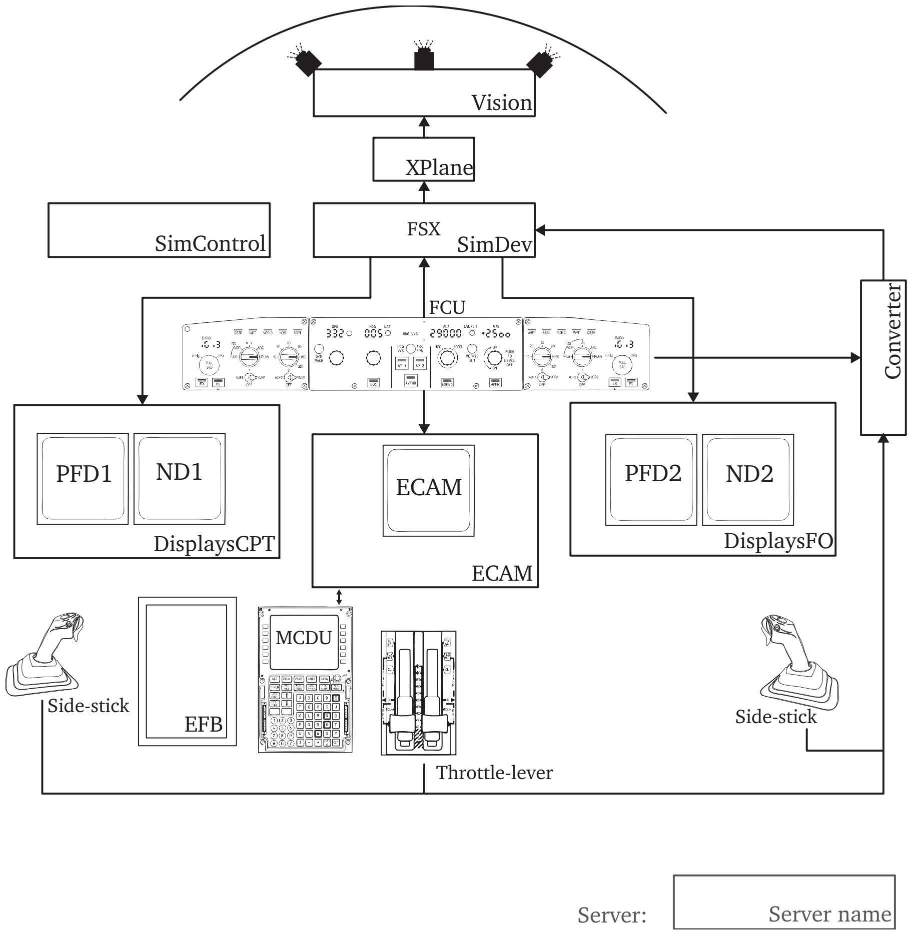


Figure 5.1.: Architecture of the research simulator

[1] Previous studies with the research simulator included: Airport Moving Maps (AMMs), synthetic vision, and tunnel in the sky applications [Ver11, Sin08, Wie06]. As these functionalities are not present at most commercial aircraft operating today, a more conservative flight deck representation, reproducing the A320 systems, was used.

side-stick and throttle lever was used to control the aircraft. For this study, the simulation environment was prepared to allow an operational integration where the pilot mostly interacts with the Multifunctional Control and Display Unit (MCDU) and Flight Control Unit (FCU) to influence the aircraft trajectory.

To fulfill the requirement of an operational A320 flight deck instrumentation, the open source software VasFMC [Vas14] was chosen and adapted to the simulator systems for this study. In total, nine servers make up the simulation environment, as illustrated in Figure 5.1. The core was formed by the flight mechanics running in MICROSOFT Flight Simulator X [Mic14] on *SimDev* with an AIRBUS A320 flight mechanics model. The position and orientation of the model was transferred to *XPlane* (using the TUD datapool [Kai01] hosted on *SimControl*, which served as the primary means to communicate data in the simulation) to process and render the outside view. For projection, the x-plane simulation [Res14] data was transferred via an x-plane function to *Vision* which projected the scenery with three projectors on mirrors for a culminated outside view. The aircraft displays were running on three servers hosting vasFMC. The Primary Flight Display (PFD) and Navigation Display (ND) were hosted on one server for each side (*DisplayCPT* and *DisplayFO*). *ECAM* displayed the upper Electronic Centralized Aircraft Monitor (ECAM) and hosted the FMS with the interface on the captain-side MCDU. *Converter* processed the flight control signals of side-stick, throttle lever and FCU, and passed the inputs to the simulation running on *SimDev*. The EFB, a Samsung slate series 7 device running G2G on Windows 7, was connected via Wireless local area network based on IEEE 802.11 standards (WiFi) to the datapool receiving basic aircraft state information from the simulation.

5.1.3 Scenario

Two routes were selected as evaluation scenarios for the trials that represent common routes within the European airspace. The first route lead from Hannover-Langenhagen, Germany, ICAO-Code (EDDV) to Palma de Mallorca, Spain, ICAO-Code (LEPA) (shown in Figure 5.2 in magenta) representing a common European charter route. The second route lead from EDDV to Sofia, Bulgaria, ICAO-Code (LBSF) (shown in Figure 5.2 in blue), representing a common European business travel route. EDDV was chosen as departure airport for both scenarios. The objective was to provide familiar European airspace scenarios. The scenario should differ from the pilots' home base, Frankfurt am Main, Germany, ICAO-Code (EDDF) for most participants.

Both routes were time constrained at two waypoints each, defining the entry and exit of a Flight Information Region (FIR). For the EDDV-LEPA route MILPA was constrained to be overflown between 11:59:50 and 12:00:10 and VATIR to be overflown between 12:35:55 and 12:36:25. These constraints served as the entrance and exit of the French airspace of the Marseille, ICAO-Code (LFMM) FIR. For the EDDV-LBSF route, ALAMU (14:09:50-14:10:10) and KEROP (14:25:30-14:26:30) were constrained to serve as interface for

Figure 5.2.: EDDV - LEPA (magenta), EDDV - LBSF (blue) created with JeppView [Jep13]

Budapest, ICAO-Code (LHCC) FIR. The small applied time windows of ± 10 seconds to ± 30 seconds are not considered realistic for the enroute flight phase, but were chosen to increase the demand for the task to guide the aircraft along the trajectory, as the simulation environment allowed only limited variations in the wind profile and the recorded evaluation flight was not to be greatly extended.

The descriptions below list the lateral routing for both scenarios with the bold part being flown during the trials.

EDDV-LEPA: HW - DV257 - ADSIN - ROLUK - TOLTA - WRB - RANAX - EDEGA - AMETU - SOGMI - BOMBI - GIGET - ABUKA - KRH - PABLA - HERBI - **MOPAN - OLBEN - LUTIX - BENOT - NEMOS - VEROX - MILPA** - GIRKU - BALSI - KOTIT - RETNO - DOTIG - GIROL - TUPOX - MTG - DIVKO - VATIR - PIVUS - MAROT - VERSO - LUNIK - D358T - CDP

EDDV-LBSF: DV157 - POVEL - ELTED - DESAR - TADUV - OSTRA - TORPU - RIVSA - DRN - RIKLU - OMELO - KOMUR - KOPIT - **ABRAX - BNO - ODNEM - BERVA - TABIN - ALAMU - PUSTA - KEROP** - TISAK - OKLOP - RAVAK - NISVA - SOF28 - D299D - SOF

5.1.4 Hypotheses and measurements

Metrics were developed to evaluate the system, and hypotheses were formulated to be compared against. Metrics are needed to evaluate these hypotheses. The hypotheses and measurements collected during the simulator trials can be categorized into the systems of the TMS they are evaluating, as shown in Table 5.1. Additionally to the evaluated TMS functionalities, LIKERT scale ratings were used on general questions regarding the trials. In the following the hypotheses and measurements for the negotiation, monitoring, and guidance functions are described.

Table 5.1.: List of metrics

	Negotiation	**Monitoring**	**Guidance**
subjective	SUS LIKERT scale System comparison	SUS LIKERT scale System comparison	SUS LIKERT scale SART NASA TLX
objective		SPAM	performance data

Negotiation

Only the briefing component of the negotiation functionality was included in the evaluation of the simulator trials[2]. It is hypothesized that the provided means to brief a trajectory on the EFB and in the FMS are usable. Furthermore it is hypothesized that the participants can retrieve the constraint information and are aware of the imposed constraints when briefing the trajectory. It is also assumed that the pilots prefer the graphical solution of the EFB compared to the textual briefing in the aircraft FMS.

H1.1.: The provided means to brief a trajectory are usable.

H1.2.: The provided means to brief a trajectory enable an awareness of imposed constraints.

H1.3.: The graphical EFB solution is providing a better trajectory briefing compared to the FMS solution.

Subjective measures and a comparison between the two means of briefing a trajectory were chosen to evaluate the briefing part of the negotiation. Subjective measures were chosen to gather the participants' opinions on their preferred system instead of confusing for example a higher remembrance rate with a better system[3]. The briefing of a trajectory integrated into G2G[4] was compared to a briefing with the aircraft FMS that was modified to allow the description of full 4D trajectories[5]. The participants performed a briefing with one of the two systems, followed by a questionnaire that included the System Usability

[2] The trajectory exchange between systems is evaluated in the Heterogeneous complex air traffic (HETEREX) and BOEING ecoDemonstrator flight trials described in Chapter 6.

[3] See Appendix A.3 and DURSO ET AL. [DRG07] for details.

[4] The realized system for briefing is described in Section 4.3.2.

[5] See Figure D.1 in Appendix D.2 for details on the modifications to the FMS.

Scale (SUS) and Likert scale ratings. This methodology was repeated for the other system on a different route, followed by a questionnaire with the same questions.

The SUS is a measure where the participants evaluate the usability on a one to five scale for ten domains. One usability score is then calculated from the answers, which can be applied in system comparisons or as a standalone rating. The Likert scale ratings were categorized in general and task specific statements. Five general statements to the usability of the systems were rated by the participants. The ratings aimed on identifying the usability of the presented information and the quality of the interaction with the system. The task specific statements were rated once for seven ratings after the initial briefing with the system, and again for the entire eight statements after performing the static flight scenario[6].

Monitoring

For the evaluation of the monitoring functionality of the TMS, the PACeR depiction was compared to a textual monitoring representation in the aircraft FMS. It is hypothesized that the PACeR depiction is usable for the pilot and that the pilot can determine the aircraft performance relative to the reference trajectory using the PACeR depiction. In addition it is hypothesized that the PACeR depiction enables a faster awareness of the performance relative to the constraint than the textual FMS representation.

H2.1.: The PACeR depiction is usable.

H2.2.: The PACeR depiction allows the determination of the performance relative to the reference trajectory.

H2.3.: The graphical PACeR depiction enables a faster awareness of the temporal performance than the FMS representation.

To evaluate these hypotheses, the SUS, Likert scale ratings, and Situation-Present Assessment Method (SPAM) response time measurements were collected and compared to the trajectory monitoring using a modified FMS. The usability was determined with the SUS. The SPAM evaluation was used to determine if the pilot was aware of the aircraft performance relative to the reference trajectory and which system (G2G or FMS) is more suitable to provide this information. The participants were handed either the EFB or the FMS with the task to identify which is the next time constrained waypoint and to decide whether or not this constraint is achievable. It was recorded if the answer was correct and the response times were measured[7].

[6] See Appendix D.3.1 for the detailed statements.

[7] The order of systems was altered as can be seen in Table D.1 in Appendix D.1 for all participants.

Guidance

Most measures were collected for the evaluation of the guidance function. There three factors were of importance:

- How demanding was it for the participants to use the system?
- How well could the participants use the system?
- How successful were the participants in performing the task they were asked to do with the system?

It is hypothesized that the guidance is usable for the pilot, that it enables the pilot to adhere to the trajectory (i.e. the set temporal constraints) and that the perceived workload of the pilot is acceptable during this task.

H3.1.: The guidance is usable.

H3.2.: The guidance enables adherence to the set temporal constraints.

H3.3.: The perceived workload ia acceptable during the guidance task.

The hypothesis that the guidance is usable, was verified with the SUS. To evaluate the performance objective performance measures from the simulator were used. The most important guidance performance measure is whether or not the pilots were able to fulfill all set objectives of the trajectory. In the evaluation scenario the objective for the pilots was to ensure the timely overflight over the enroute Trajectory Change Points (TCPs) ALAMU and KEROP with an allowed deviation of ±10 s at ALAMU and ±30 s at KEROP which can be used as objective for the analysis.

The workload of the guidance task is measured as perceived workload from the pilot. The National Aeronautics and Space Administration (NASA) Task Load Index (TLX) was applied as subjective workload measurement tool, which differentiates the perceived workload in six dimensions [HS88]. The pilot rates the performance in each dimension on a 0-100 scale. This measurement was verified by a Likert scale rating asking directly for the perceived workload.

In addition the SA of the participants in the guidance situation was rated with the Situation Awareness Rating Technique (SART) where the participants rate statements on a seven point scale from low to high.

5.2 Trial execution

The simulator trials took place over a three week period, from November 18 to December 5, 2013. The following Section provides an overview of the participant group and the individual sequence of events during the evaluation.

5.2.1 Participant group

Seventeen male pilots participated in the study[8]. All pilots held an Airline Transport Pilot License (ATPL), with sixteen of the pilots holding a type rating for a commercial aircraft. Six participants had a type rating for the Airbus A320 aircraft family, two participants each held ratings for the Airbus A330/340 family, the Airbus A380, Boeing 737 family, and Boeing 747-400. One participant was holding a type rating for an Embraer 190 and one participant finished flight school but did not yet hold a type rating. In addition to their ATPLs four pilots held engineering degrees, and one pilot was a medical practitioner. The age of the participants ranged from 25 to 66 years old (μ= 41.2 years; σ= 11.5 years). Nine pilots were holding the position of Captain (CPT) (one retired), two of a Senior First Officer (SFO)[9], and six of a First Officer (FO). The experience ranged from 160 to 21,000 flight hours (μ= 9,280 hours; σ= 6,107 hours). Fifteen participants were flying for Lufthansa, one for Air Berlin, and one recently finished flight school. Fifteen of the participants claimed to have had previous experience with an EFB and ten with the RTA functionality of the FMS. Four methods of recruiting were used. Invitations were placed via Vereinigung Cockpit[10] to all active members and via the Lufthansa intranet for flying personnel placed by their A320 fleet chief. In addition, a list of pilots who participated in previous evaluations from Jeppesen and personal contacts were used to recruit pilots directly. None of the participants were paid to participate in the study[11].

5.2.2 Sequence of events

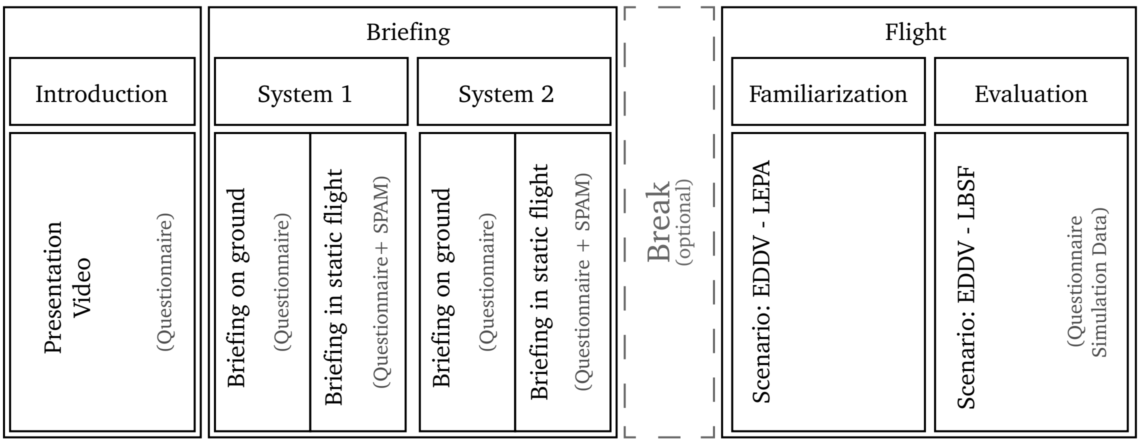


Figure 5.3.: Sequence of events for an individual trial

8 See Table D.1 in Appendix D.1 for a complete list of participants.

9 The SFO replaces the CPT in cruise on long haul flights during the rest periods of the CPT.

10 Vereinigung Cockpit is the German pilots' union.

11 The participation without compensation indicates a high interest in future developments and technologies.

The sequence of events is illustrated in Figure 5.3 for each evaluation run. Each participant received an individual introduction to the trials in the institute's conference room. Each participant was given an overview of the agenda, an overview of trajectory management, an overview of G2G, and completed the first part of the evaluation. In addition, a video summarizing the HETEREX flight trials[12] was shown to the participants to describe the operational vision of a retrofit TMS. After initial questions were clarified, the pilots filled out the front page of the questionnaire with general questions regarding each participant's background.

The system evaluation started in the research flight simulator with the first part comparing two means to brief a trajectory: the JEPPESEN G2G application and the expanded flight plan in the FMS briefed via the MCDU and ND allowing the definition of flexible "**between**" time constraints[13]. Both systems were evaluated on the ground and in a static enroute situation. The ground evaluation had the participants familiarize themselves with the system, the loaded route, and the set time constraints along the route. From the static flight situation, the pilot was given the task to identify the next time-constrained waypoint and to decide whether or not this time constraint was feasible. The pilot was handed the system after clarifying the task and the response time of the pilot to identify the aircraft performance relative to the reference trajectory was measured. Both, the order of systems (system 1 and system 2), and used scenario, as well as the position for the static flight (and therefore the possibility to meet the next time constraint or not), were altered among the participants as independent variables. Each situation evaluation was followed by a questionnaire for the participants.

An optional break was offered after the briefing part of the evaluation. Approximately half of the participants took the break, allowing additional discussions and rest before the second part of the evaluation.

After the break, the second part of the evaluation began with a familiarization scenario using the time control functionality in G2G to control the aircraft executing a full 4D trajectory. A route from EDDV to LEPA served as familiarization scenario. After the pilots were familiar with the system, the evaluation scenario from EDDV to LBSF was started and the simulation data recorded. The flight started enroute to LBSF before the first constrained waypoint and was conducted until the LHCC FIR was crossed and the second constrained waypoint (KEROP) was overflown[14]. There, the simulation was stopped and the simulation performance data collected. Afterwards a last summarizing questionnaire was filled out by the pilot. This concluded the evaluation, which took about three hours per participant.

[12] Compare to Section 6.2.

[13] See Appendix D.2 for details on the modifications.

[14] Compare to the routing detailed in Section 5.1.3

5.3 Analysis

The analysis of the data collected in the trials is divided into four Sections: Three Sections discussing the data for each of the TMS functionalities of trajectory negotiation, monitoring and guidance, and a general section analyzing the overall simulation environment.

5.3.1 Negotiation

The negotiation functionality of the realized TMS is evaluated by comparing a TMS integrated into the aircraft FMS measuring the usability and LIKERT scale ratings.

Usability

The usability of the two TMSs for the negotiation was evaluated using the SUS. The scores for both systems are shown in Figure 5.4 as box plots. The FMS was ranked slightly higher (μ= 89.4; σ= 15.1) than G2G (μ= 80.1; σ= 13.5). A system with an average rating of above 68 is considered usable [Sau11], which is the case for both systems. For the FMS and G2G two ratings each are below this threshold.

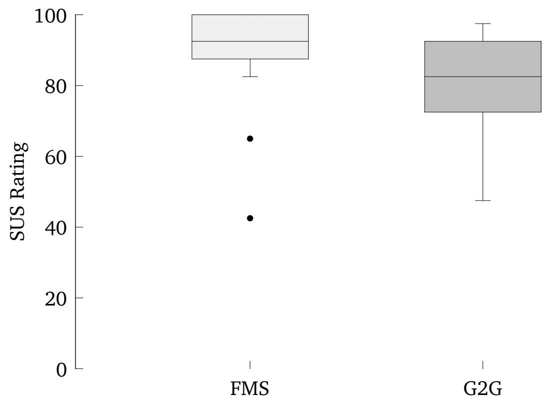


Figure 5.4.: SUS rating briefing for FMS and G2G

As the SUS scale ratings are described as ordinal variable, a Mann-Whitney-Test was applied which identified that the difference between the systems was statistical significant (p=0.013). A significance level of $\alpha = 0.05$ was used in the assessment that will be applied in all statistical tests within this work. When comparing the ratings within the SUS, statistical significant[15] differences can be identified for statement 4, 9, and 10[16]. Statements 4 and 10 focus on the learnability of the system ("need support of a technical person"/"need to learn a lot"). The higher ratings of G2G to these statements indicate

[15] The result is only statistical significant when not corrected for multiple testing, such as by a BONFERRONRI corrections and may indicate a false positive.

[16] See Appendix D.3 for the detailed analysis data.

the lower degree of familiarity with the G2G system. This lower degree of familiarity might have also led to a significantly lower rating of statement 9 for the G2G system "I felt confident using the system".

Ratings

In order to gather additional pilot feedback, statements were rated by the participants on a LIKERT scale. These ratings can be categorized into general and task-specific ratings.

General Ratings

Only the statement "The control of the system was self-evident" revealed a statistical significant difference between the two systems[17]. With G2G receiving a slightly lower rating on average (FMS: $\mu = 4.71$; $\sigma = 0.77$; G2G: $\mu = 4.12$; $\sigma = 1.11$).

Task-specific ratings

Both systems were rated positive in respect to the provided usability statements with only a statistical significant difference[18] between the two systems in statement three ($p=0.022$ for briefing, and $p=0.041$ for static flight.), "I needed assistance in solving the task.". For both scenarios, the statement was disagreed for both systems on average, but the G2G system had a higher degree of agreement (FMS: $\mu = 1.39$; $\sigma = 1.01$; G2G: $\mu = 2.17$; $\sigma = 1.46$).

5.3.2 Monitoring

The analysis of the monitoring functionality is structured into the usability, LIKERT scale ratings, and the assessment of the participants SA.

Usability

The usability of the monitoring functionality was rated using the SUS. As only one monitoring system was evaluated, the SUS rating serves as absolute subjective usability measurement. The monitoring functionality of the TMS received a mean SUS score of 82.6 ($\sigma = 15.6$), which is above the threshold 68 where systems are considered usable [Sau11]. Three pilots rated the monitoring functionality below this threshold. The learnability was rated higher with a mean score of 86.0 ($\sigma = 17.0$), which is slightly higher than the usability component of the SUS ($\mu = 81.8$; $\sigma = 16.3$).

17 The difference is only significant without a multiple testing correction. See Appendix D.3 for the detailed analysis.

18 The difference is, again, only statistically significant without considering a possible false positive caused by the multiple testing problem. See Appendix D.3 for the detailed analysis data.

Ratings

The PACeR depiction was evaluated by the pilots using LIKERT scale ratings[19]. The results are shown in Figure 5.5 as box plots. All but two pilots had confidence in the monitoring information presented (μ= 4.5; σ= 0.7). Only one pilot disagrees with the statement that the PACeR was intuitive and easy to understand (μ= 4.1; σ= 1.0). Three pilots disagree that the PACeR increases their temporal SA (μ= 3.8; σ= 1.2). When asked about the differentiation of the envelope and economic PACeR no pilot stated not being able to differentiate between the two depictions (μ= 4.5; σ= 0.7) and only one pilot disagrees that this differentiation aids in decision-making (μ= 4.1; σ= 1.0).

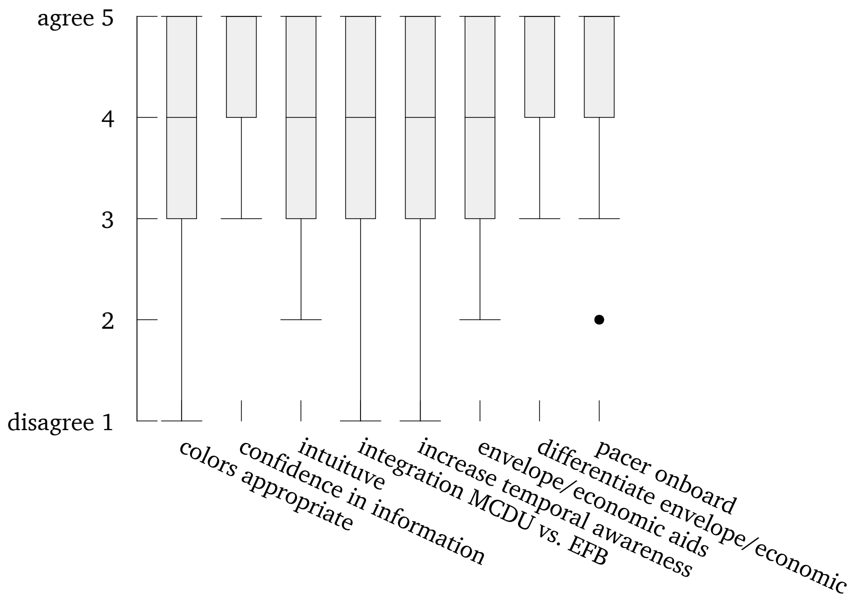


Figure 5.5.: Monitoring ratings

The colors used in the PACeR depiction were rated quite mixed. Nine pilots agreed that the colors were appropriate, five pilots were undecided and three disagreed (μ= 3.5; σ= 1.3). The mixed response may have various reasons due to the miscellaneous group of pilots. Three groups can be differentiated, pilots not familiar with the AIRBUS color scheme, AIRBUS pilots who noticed the AIRBUS color scheme and approved it, and other pilots who also noticed the color scheme but did not think it was good for an EFB system as this display is independent of the aircraft systems and has more potential in depicting colors and graphics[20].

All but two pilots would like to have the PACeR feature onboard their aircraft when operating in a Trajectory-Based Operations (TBO) environment (μ= 4.5; σ= 0.8). The

[19] For the detailed ratings see Figure D.6 in Appendix D.3.2.

[20] See the open feedback provided in Appendix D.3 for details.

question if an integration of the PACeR depiction into the navigation display instead of the EFB was answered inconclusive (μ= 3.6; σ= 1.3). Ten pilots preferred an integration into the aircraft ND, four preferred an integration on the EFB, and three favored an integration in both systems.

Situation Awareness

All pilots answered all questions of the SPAM correctly for both systems. As can be seen in the box plot in Figure 5.6 shows that the mean response times were longer for the G2G system (μ= 49.7 s; σ= 25.1 s) than for the FMS (μ= 20.3 s; σ= 12.8 s). The response times for the MCDU system are not normally distributed (Shapiro-Wilk p=0.002). Therefore, a Mann-Whitney test was applied, which identified statistical significant differences between the response times of the two systems (p<0.001).

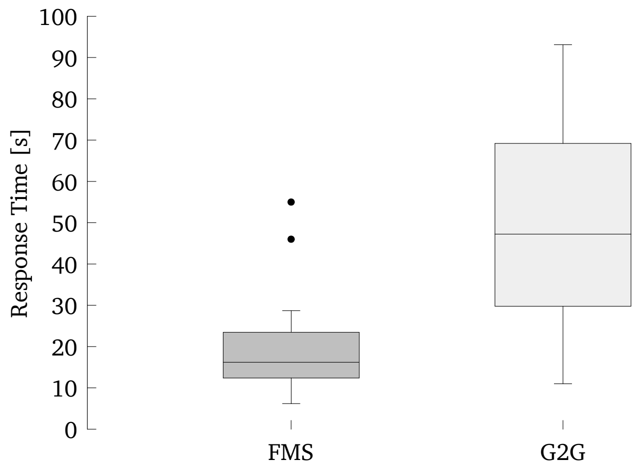


Figure 5.6.: Response times

One possible explanation for the significantly shorter response times using the FMS might be the familiarity with the system. One pilot stated: "Working with the MCDU for more than 15 years made this task very easy to solve." The pilots did not have this degree of familiarity with G2G, which all of them saw for the first time on the day of the test.

5.3.3 Guidance

The following Section contains the analysis of the guidance function of the TMS divided into the usability, SA, workload, general LIKERT scale ratings, and the performance results.

Usability

Guidance usability is rated similar to the monitoring functionality, with the SUS as absolute measurement. The guidance functionality was rated with a mean of 83.2 (σ= 13.9), which is similar to the monitoring function as "most usable". Three pilots rated the guidance function below the threshold of 68 for a usable system. The learnability received a higher rating (μ= 91.2; σ= 17.0) than the usability rating part of the SUS (μ= 81.3; σ= 14.3).

In the open feedback a number of pilots mentioned additional information they would like to have included in the guidance bar to aid in decision making[21] (e.g. distance to the next constrained TCP and the current time). Since this information was not available, it might have led to a slight downgrade of the SUS rating.

Situation Awareness

The results of the SART are shown in Figure 5.7 as box plots. The majority of the participants (76%) rated the guidance situation as stable (μ= 2.7; σ= 1.7) and all pilots rated it as having a low complexity (μ= 1.9; σ= 0.7). All but one participant rated the variability of the guidance situation as low (μ= 2.2; σ= 0.9) and only one participant noted a high arousal during the task (μ= 2.5; σ= 1.3). Two participants noted an above-average level of concentration of attention (μ= 2.6; σ= 1.2) and division of attention (μ= 2.6; σ= 1.2). All but two participants noted a high level of spare mental capacity (μ= 5.3; σ= 1.7). The rating of information quantity (μ= 5.3; σ= 1.8) and familiarity with the situation (μ= 4.7; σ= 1.8) differed among the participants with mean high ratings on both.

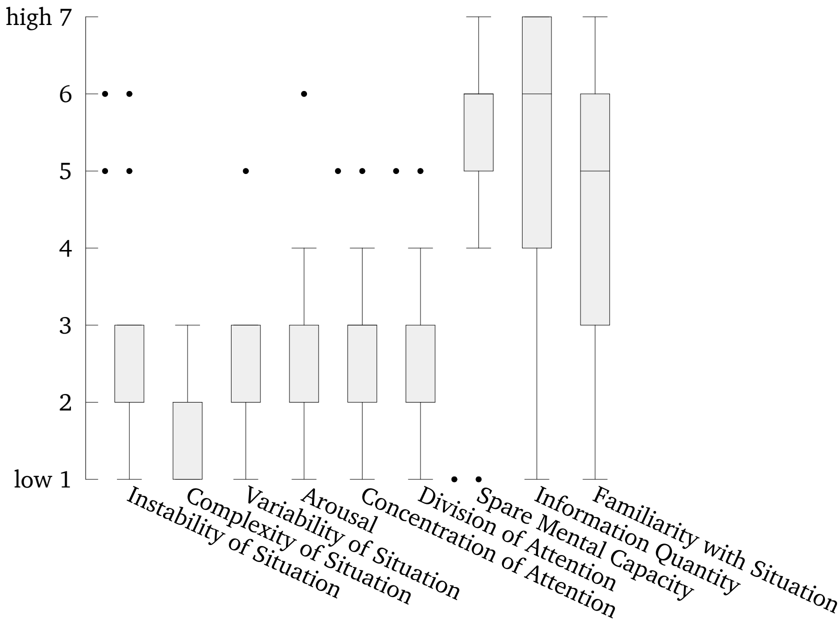


Figure 5.7.: Guidance SART

[21] See the open feedback in Appendix D.3 for details.

Workload

The results of the NASA TLX are shown as a box plot in Figure 5.8. All domains but performance have a mean rating below 17, with the mean performance rating above 95 on a scale from 0 - 100 (Mental Demand: μ= 16.2; σ= 9.6 - Physical Demand: μ= 6.5; σ= 5.4 - Temporal Demand: μ= 10.3; σ= 8.7 - Performance: μ= 95.6; σ= 6.4 - Effort: μ= 14.1; σ= 12.3 - Frustration: μ= 4.4; σ= 6.2).

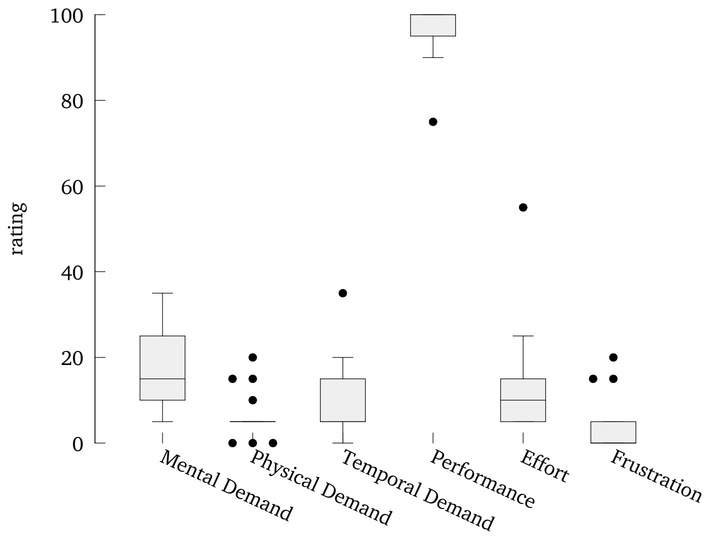


Figure 5.8.: Guidance NASA TLX

These low perceived workload ratings are confirmed by the LIKERT scale question, where all but one pilot agree to the statement "The perceived workload is acceptable during the guidance task." One pilot was undecided (μ= 4.7; σ= 0.57), as shown in Figure D.7(g).

Ratings

LIKERT scale ratings were used[22] for a structured collection of pilot feedback to the realized guidance system and pilot tasks in execution. The results are shown in the box plots in Figure 5.9. All seventeen participants agreed that they had confidence in the presented guidance information (μ= 4.5; σ= 0.5). Two pilots believed that the task they performed of manual 4D guidance could not be performed in an operational environment (μ= 4.2; σ= 1.0), one pilot was undecided. Asked about the information quantity, two pilots disagreed that the guidance bar provided all information they needed to perform the guidance task (μ= 4.2; σ= 1.0) and all but two pilots disagreed that information the pilots do not need is displayed (μ= 1.5; σ= 0.8). Similar to the color use in the monitoring functionality, the use of colors in the guidance bar was rated "mixed," with four pilots

[22] See Figure D.7 in Appendix D.3.3 for details on the distribution of the answers.

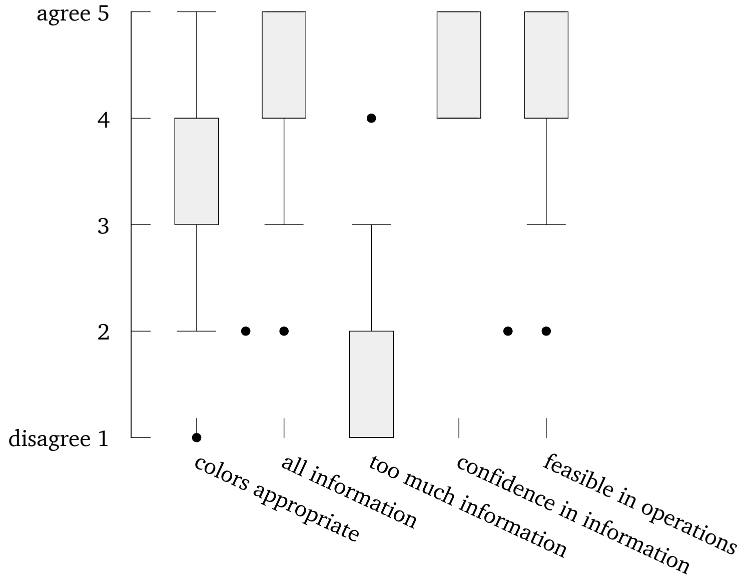
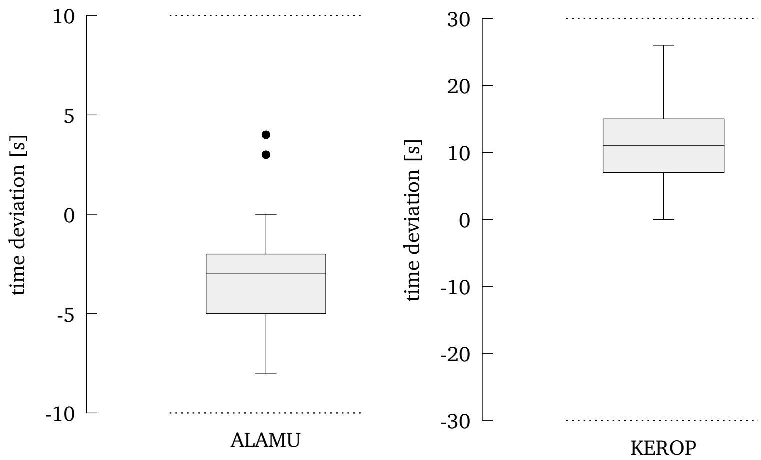


Figure 5.9.: Guidance ratings

disagreeing and nine pilots agreeing. The remaining four rated the statement "neutral" (μ= 3.5; σ= 1.2).

Performance



(a) Performance ALAMU (b) Performance KEROP

Figure 5.10.: Performance of time constraint adherence

All pilots adhered to both temporal objectives in the evaluation scenario. Figure 5.10 illustrates the overflight times at both waypoints relative to their temporal constraints as box plots. ALAMU was overflown, on average, later than the target time, as the time constraint required the aircraft to accelerate from the initial condition and the objective was to meet the time window but not specifically in the middle of the defined time window (μ= -2.9 s; σ= 3.1 s). For KEROP all pilots arrived earlier than the mean target time but within the constraint window (μ= 11.1 s; σ= 7.6 s). The larger Standard Deviation (SD) reflects not only the larger time constraint window but also the different strategies the pilots used in guiding the aircraft along the trajectory (arriving in the middle of the time window to increase flexibility vs. arriving as early as possible to reduce speed changes).

In addition to adhering to the objectives, it is interesting to observe how the pilots achieved this performance. During the evaluation run, the pilots were shown three to six recommended Mach number changes in the G2G application (μ= 4.6; σ= 1.0). The pilots reacted to these recommendations with five to seventeen Mach number changes entered into the aircraft FCU (μ= 8.0; σ= 3.8). The flown trajectories had an average Ground Speed (GS) deviation to the reference guidance trajectory of 3 kts to 19 kts, which also indicates the different strategies in the trajectory execution (μ= 11.8 kts; σ= 4.6 kts). As a result, the Estimate Time of Arrival (ETA) of the constrained TCP was outside the RTA window for 3.8% to 22.2% of the flights, depending on the strategy used (μ= 9.2%; σ= 5.9%).

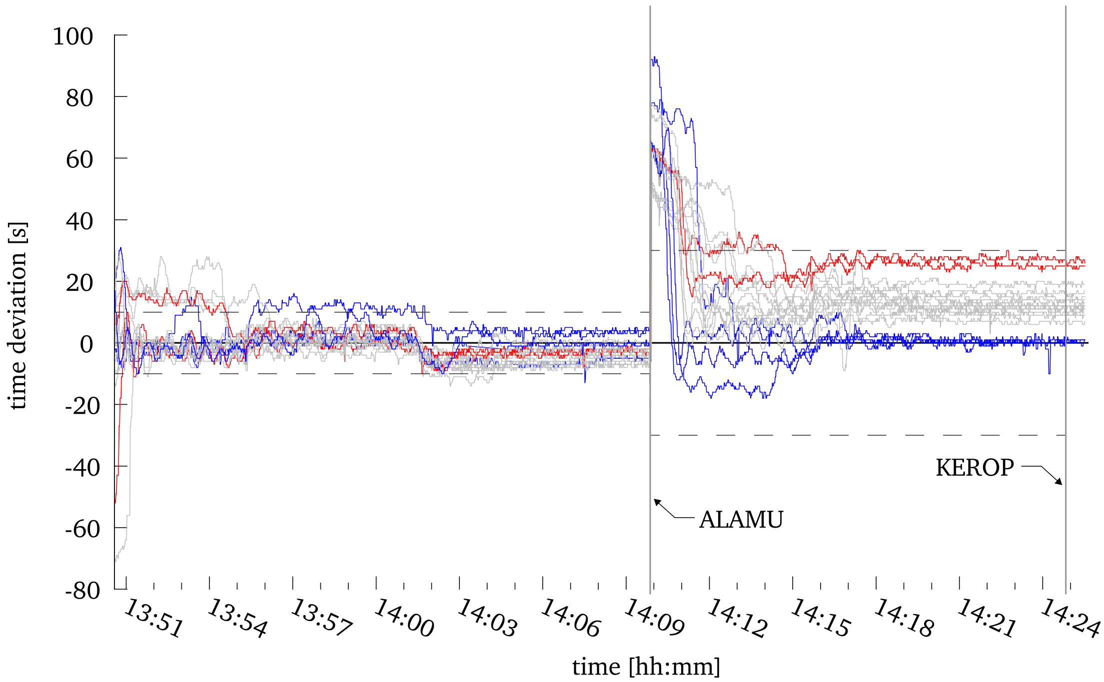


Figure 5.11.: Time deviation along trajectory

The temporal deviation (mean RTA - ETA) is shown for the seventeen evaluation runs in Figure 5.11. In the left part the ±10 second constraint at ALAMU was active as illustrated by the dashed lines. Depending on the initial condition a longer transient state can be observed at the beginning. After passing ALAMU the guidance switched to the ±30 seconds constraint at KEROP this required a change in speed for all flights which can be seen from the spike in time deviation after passing ALAMU. The pilots were required to decelerate the aircraft to meet the constraint at KEROP. Although the trajectories differed for each flight, three strategies for meeting the KEROP time constraints can be identified. Two pilots followed an aggressive strategy, arriving early at KEROP illustrated in Figure 5.11 in red. Ten out of the seventeen illustrated trajectories followed a moderate approach, balancing the time savings by arriving early at KEROP with the speed reduction after passing ALAMU. These trajectories are illustrated in gray. Four pilots followed a flexible strategy trying to meet the time constraint window exactly at the mean illustrated in blue. For this strategy, the pilots used an above average amount of Mach number changes ($\mu = 11.5$; $\sigma = 3.5$), where the pilots using the aggressive strategy used a below-average number of mach changes ($\mu = 5.0$; $\sigma = 0.0$). The black dashed line illustrates the RTA time window in which the ETA had to be confined when crossing a constraint waypoint to meet the objectives of the trajectory, which is the case for all flown trajectories after a transient phase.

5.3.4 General

General LIKERT scale ratings and open feedback were gathered to determine the applicability of the flight trial results.

Ratings

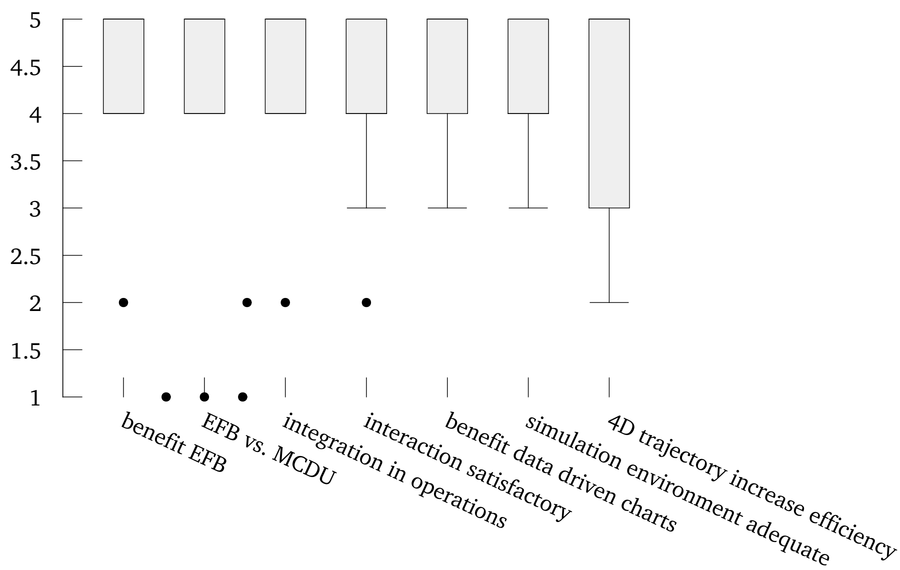


Figure 5.12.: General ratings

The majority of pilots agreed to the statements in Figure 5.12. All but one pilot saw a benefit of using an EFB in the trajectory management ($\mu = 4.5$; $\sigma = 0.8$). Fourteen out of the seventeen pilots prefer the EFB for a trajectory briefing over the MCDU ($\mu = 4.0$; $\sigma = 1.5$). All but two pilots believe that the tasks performed in the evaluation can be performed in today's operational environment ($\mu = 4.4$; $\sigma = 1.0$). The concept of interaction with the EFB was considered satisfactory by all but two pilots, confirming the high SUS ratings for the different functionalities ($\mu = 4.2$; $\sigma = 0.8$). Pilots did not see the benefit of seamless data-driven charts compared to the charts they currently use ($\mu = 4.5$; $\sigma = 0.7$). All but two pilots agreed that the simulation environment was adequate for the study ($\mu = 4.4$; $\sigma = 0.7$). Two pilots do not believe that 4D trajectories would increase the efficiency of the Air Traffic Management (ATM) system ($\mu = 4.1$; $\sigma = 1.0$).

The pilot responses to these statements confirm the previous results to the TMS functionalities: the approach to a retrofit TMS based on an EFB, the validity of the simulation environment and the need for further development of data-driven charts to support functionalities among them those of a TMS.

Open Feedback

To complement, open feedback was collected using the questionnaire after each experiment and through comments from the participants during the experiment runs[23].

Much of the feedback concerned the interface design of G2G, such as color use and recommendations for displaying certain information. This feedback could help to refine the interface in a further iteration, but most of the feedback represents a pilot's opinion and preferences.

Three pilots remarked that they already have use cases requiring adherence to time windows at TCPs[24]. Even though they have the RTA functionality of their FMS[25] available, prefer to iterate through Mach speeds or Cost Index (CI) manually to fulfill the constraint. The control of RTA functionality is perceived to reduce passenger comfort[26] and fuel economy because of frequent speed changes.

5.4 Discussion

The simulator trials in the TUD research flight simulator evaluated the three functionalities of a retrofit TMS: negotiation, monitoring, and guidance. The following Section discusses the results of the working hypotheses defined in Section 5.1.4 evaluated with the data from the simulator trials.

[23] The entire open feedback from the pilot questionnaires is listed in Appendix D.3.

[24] Examples mentioned were the entry into the North Atlantic Tracks (NAT) system, and entry into the airspace over Afghanistan controlled by the Bay of Bengal Cooperative Air Traffic Flow Management System (BOBCAT) and not arriving too early (before the end of the curfew) in EDDF.

[25] Compare to Section 2.4.

[26] Passenger comfort is among the five major objectives of a commercial flight [EFJ+98].

5.4.1 Negotiation

The negotiation functionality is evaluated on the three set hypotheses for usability (H1.1.), constraint awareness (H1.1.) and preference of the system for briefing (G2G or FMS) (H1.3.).

Although receiving a significantly lower rating than the FMS for the negotiation, the G2G negotiation functionality received a SUS score of 80.1, which is above 68, the score for which a system can be defined as usable [Sau11]. Two individual ratings were below this score. With a usability rate for more than 88% of the participants the hypothesis of a usable briefing functionality (H1.1.) is not rejected.

The hypothesis of the constraint awareness is rated on the responses of the pilots when asked to name the constraints of the trajectory. All pilots were able to name all time constraints for the briefing on ground and for static flight (see Section 5.3.2). Therefore the hypothesis for constraint awareness (H1.2.) is not rejected.

The hypothesis of a preference of the participants for the G2G representation over the FMS integration cannot be supported by performance or other measures which have shown no benefit of G2G over the FMS in the performed tasks (response times, SUS and LIKERT scale ratings). Therefore the hypothesis that the graphical solution in G2G provides better means to brief a trajectory than a textual representation in the FMS (H1.3.) is rejected. However, fourteen out of the seventeen pilots preferred the graphical briefing on the EFB. This direct statement indicates a preference of the G2G application for the trajectory briefing, which was not backed up by other measures in the evaluation.

5.4.2 Monitoring

The monitoring functionality of the PACeR in the realized TMS is evaluated on the three set hypotheses for usability (H2.1.), the determination of the performance with the PACeR (H2.2.) and a faster performance determination than with a textual representation in the FMS (H2.3.).

The monitoring system received a SUS score of 82.6, which is above the threshold of 68 for a usable system [Sau11]. Three participants rated the system below the threshold. This translates into a usability rate for above 82% of the participants, therefore the hypothesis of a usable system (H2.1.) is not rejected.

All pilots were able to determine in the static flight situation if the next time constraint would be achievable and if not if they were too late or too early (see Section 5.3.2). Therefore the hypothesis that the PACeR enables the pilot to determine the aircraft performance relative to the reference trajectory (H2.2.) is not rejected.

Comparing the times needed to determine the aircraft performance relative to the reference trajectory with the PACeR depiction in G2G to the depiction in the FMS the PACeR depiction shows significantly slower reaction times indicating a higher awareness using the FMS system. Therefore the hypothesis of a higher performance awareness using the

PACeR (H2.3.) is rejected. However, twelve out of the seventeen participants agree that the PACeR increases their temporal SA, and fifteen participants would like to have the feature on board. This agreement indicates as for the briefing capability in G2G that the pilots see a benefit in the graphical integration of the TMS in G2G which was not measured by performance measures during the evaluation.

5.4.3 Guidance

For the guidance functionality three hypotheses were formulated regarding the guidance function usability (H3.1.), performance to fulfill temporal constraints along the trajectory (H3.2.) and that the perceived workload of the pilot is acceptable (H3.3.).

The guidance system received a SUS score of 83.2 which is above the threshold of 68 for a usable system [Sau11]. Three pilots rated the usability of the guidance function below this threshold. This translates into a usability rate of 82%. Therefore the hypothesis for a usable guidance system (H3.2.) is not rejected.

All pilots adhered to all set time constraints of the trajectory (see Section 5.3.3). Therefore the hypothesis for a temporal constraint adherence (H3.3.) is not rejected.

The perceived workload was rated by a NASA TLX, which showed low ratings in all domains but performance. This translates into an acceptable perceived workload therefore the hypothesis (H3.3.) is not rejected. In addition all but one pilot rated their perceived workload as acceptable on a Likert scale rating.

5.4.4 Summary

The trials in the TUD research flight simulator demonstrated that the participants could perform the tasks required in the evaluation with the realized TMS. The evaluation consisted of two parts, for which two routes were used (EDDV-LBSF and EDDV-LEPA). One static test compared the negotiation and monitoring functionality of G2G to the FMS, on the ground and in a static flight situation. A dynamic flight task was used to evaluate the guidance functionality and gathered additional operational feedback.

The trials were performed with seventeen pilots to evaluate the defined working hypotheses with subjective and objective measures. Seven out of the nine defined hypotheses[27] were not rejected as is summarized in Table 5.2. All functionalities of the realized TMS were rated as usable, and feedback was provided to further iterate the color scheme and depiction of elements. The PACeR depiction did not provide a measurable higher temporal constraint awareness than the textual information in the FMS. Also the graphical briefing in G2G showed no significant benefit over the textual FMS representation for the tasks evaluated. One possible explanation is the lower degree of familiarity the pilots had with the G2G EFB application than with the FMS for the task they were asked to perform.

[27] Compare to Section 5.1.4.

Table 5.2.: Overview of evaluated hypotheses

H1.1.	The provided means to brief a trajectory are usable.	✓
H1.2.	The provided means to brief a trajectory enable an awareness of imposed constraints.	✓
H1.3.	The graphical EFB solution is providing a better trajectory briefing compared to the FMS solution.	x
H2.1.	The PACeR depiction is usable.	✓
H2.2.	The PACeR depiction allows the determination of the performance relative to the reference trajectory.	✓
H2.3.	The graphical PACeR depiction enables a faster awareness of the temporal performance than the FMS representation.	x
H3.1.	The guidance is usable.	✓
H3.2.	The guidance enables adherence to the set temporal constraints.	✓
H3.3.	The perceived workload ia acceptable during the guidance task.	✓

The analysis determined that guidance of the aircraft is not primarily a control task, but rather, an optimization task. Instead of presenting the pilot guidance cues, a CI optimization tool taking time constraints into account was seen as beneficial. The system could inform the pilot when larger deviations occur. An incorporation into fuel/time checks performed already today is assumed to be sufficient to fulfill the envisioned enroute full 4D time constraint windows of approximately 2-3 minutes.

6 System evaluation during flight trials

Flight trials were conducted to demonstrate the operational feasibility and evaluate the developed system under real world conditions. The flights were performed onboard two aircraft: the BOEING ecoDemonstrator, a BOEING 737-800, and the DEUTSCHES ZENTRUM FÜR LUFT- UND RAUMFAHRT E.V. (DLR) Advanced Technology Research Aircraft (ATRA), an AIRBUS A320-232 within the German research project Heterogeneous complex air traffic (HETEREX) [Hin09]. These aircraft shown in Figure 6.1 represent two aircraft families that make up more than half of the world-wide commercial aircraft fleet[1]. The trials took place in the United States and in Europe where in total more than half of the worldwide commercial aircraft fleet is operating [Boe13].

(a) BOEING ecoDemonstrator

(b) DLR ATRA

Figure 6.1.: Test aircraft

This Chapter discusses both the BOEING ecoDemonstrator and the DLR HETEREX flight trials, the objectives and scenarios are presented, and results analyzed.

6.1 Boeing ecoDemonstrator flight

As part of the BOEING ecoDemonstrator test flight campaign [Nor12], a flight from Reno-Tahoe International Airport, NV, ICAO code (KRNO) to Glasgow Industrial Airport, MT, ICAO-Code (07MT) was completed with trajectory advisory cues displayed on the Gate-to-Gate (G2G) demonstrator. The test flight took place on September 16, 2012, from

[1] 5,407 out of the produced 7,604 BOEING 737 family aircraft were in service in December 2011 [Bro11] as well as 5,597 aircraft of the AIRBUS A320 family in May 2013 [Air13b] together these aircraft families make up approximately 57% of the 18,890 commercial aircraft in service in July 2010 [Hin10]. Note the uncertainties in as a result of their differing validity dates.

07MT to KRNO, and, after a short stop in KRNO, returned to 07MT. The G2G application was used during both flights to demonstrate inflight Weather (Wx) and Notice to Airmen (NOTAM) updates, along with an inflight re-routing on an integrated, data driven supplemental aeronautical information display with wireless onboard connectivity. On the return leg to 07MT G2G was used as 4D arrival guidance display using the Continuous Descent Approach for Maximum Predictability (CDA-MP) guidance principle detailed in Section 3.5.3 with the interface described in Section 4.5.2.

6.1.1 Objective

The objective of the ecoDemonstrator arrival into 07MT was to demonstrate the negotiation, calculation and communication of a continuous 4D trajectory as well as to evaluate the adherence thereof, using the CDA-MP guidance principle through the depiction of guidance cues on an Electronic Flight Bag (EFB).

In detail, the test flight should examine the following six objectives of the CDA-MP trajectory management and guidance system:

- **Feasibility:** Test the feasibility of trajectory negotiation, generation, and adherence, under real-world conditions.
- **Stability:** Appraise the stability of the flight guidance.
- **Robustness:** Confirm the robustness of the guidance to external disturbances.
- **Accuracy:** Determine the accuracy of the guidance in terms of vertical and time deviations.
- **Ride quality:** Evaluate the ride quality for passengers.
- **Usability:** Determine the usability for the pilot.

6.1.2 Scenario

The scenario for the Boeing ecoDemonstrator was a descent into 07MT with the CDA-MP guidance principle displayed in G2G. The following Sections detail the routing, test procedures, and hardware integration for the flight, with an overview of the collected measurements to determine the performance in the six objectives of the flight.

Routing

The routing was selected in coordination with the Salt Lake City Air Route Traffic Control Center (ARTCC) to avoid the HAYS Military Operations Area (MOA) south-west of 07MT, which extends from 300 ft Above Ground Level (AGL) to 18,000 ft Mean Sea Level (MSL), and would therefore limit a direct Continuous Descent Approach (CDA) into 07MT.

Descent 1 GTF - LEWIT - HILGR - COKEE - GGW - D266W - ILS RWY 10

Descent 2 07MT - GGW - (V430) KEEVR - BOWDN - CAGAT - IVIVE - ISITE - HVR - (V257) YOYNO - BELCA - SHONK - PSHKN - CARBO - GTF - LEWIT - HILGR - COKEE - GGW - D266W - ILS RWY 10

The routing for the initial arrival from KRNO started at Great Falls MT, VOR (GTF), turning eastbound to COKEE via LEWIT and HILGR. From there, the route turned northbound to Glasgow MT, VOR (GGW), followed by a turn westbound to the Initial Approach Fix (IAF) D266W of the approach[2]. This routing is illustrated in Figure 6.2.

Three descents total were planned, if the availability of the aircraft would permit. For this, the aircraft would not have landed, but would have performed a go-around procedure on the missed approach to GGW, turned right on airway V430 to Havre MT, VOR (HVR), and from there, to GTF via airway V257 where cruising altitude would reached again, and the descent would follow as in the previous arrival.

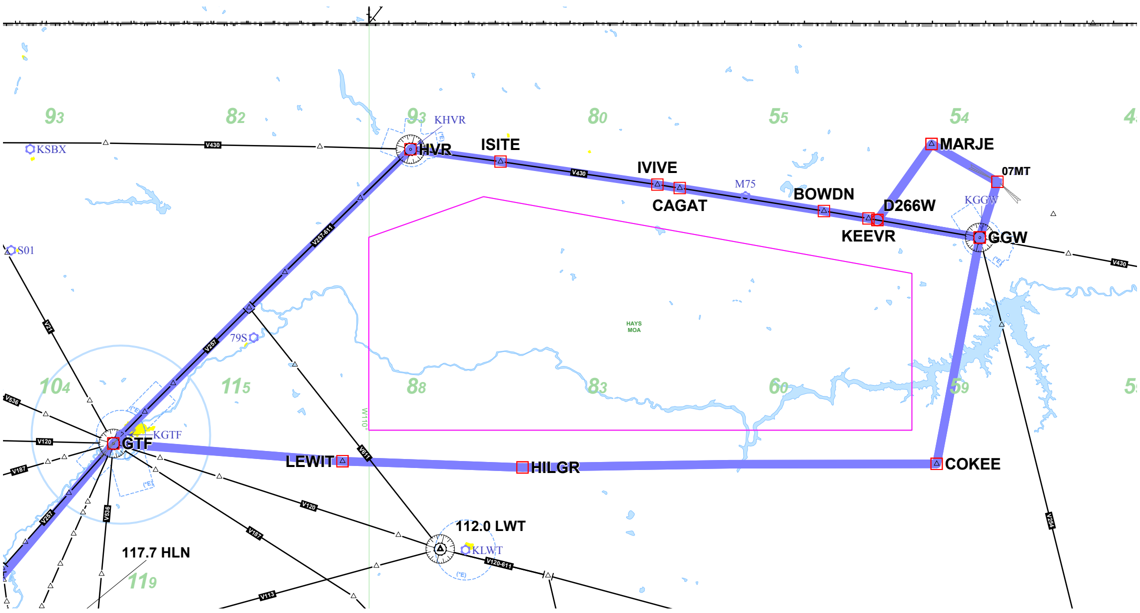


Figure 6.2.: Route for Boeing ecoDemonstrator flight into 07MT created with JeppView [Jep13]

Test procedure

The test plan was to start with the onboard request of a descent trajectory from the Airline Operations Center (AOC)[3], about 20 NM after passing HILGR. Once the trajectory calculated on ground would be received, it would be followed, including the initiation

[2] See Figure E.5 in Appendix E.1.2 for a chart of the approach procedure.

[3] The Jeppesen office in Gdansk, Poland served as AOC for this test point.

of the Top of Descent (TOD). The flight would then follow the guidance until reaching an altitude of 10,000 ft. This would ensure enough time to stabilize the aircraft for the approach into 07MT.

Hardware integration

The G2G application was integrated into the Boeing ecoDemonstrator using the communication architecture defined in Section 4.1 and described in more detail in Appendix E.1. G2G was running on a Hewlett Packard (HP) rack mounted computer with connectivity via SwiftBroadband satellite data link through a Secure Sockets Layer (SSL)-Virtual Private Network (VPN) to a ground server acting as AOC in Gdansk, Poland. A read access to the Flight Management System (FMS) was established through the Onboard Network System (ONS) via a JavaScript Object Notation (JSON) data format. An Apple iPad served as EFB class 2. It was coupled as external touchscreen to the HP server connected via Wireless local area network based on IEEE 802.11 standards (WiFi) using the application iDisplay [sha13]. The integration of the iPad mounted in the cockpit is depicted in Figure 6.3.

Figure 6.3.: iPad integrated into ecoDemonstrator cockpit

Measurement

During the flight execution, objective and subjective measures were collected to determine the performance and usability of the system. The feasibility, stability, robustness, and accuracy could be measured from the performance, determined by the aircraft state vector, of the flown trajectory. The ride quality and usability were subjective to the passengers and pilots. Therefore, the pilots were asked about their impression on the usability after the flight, their comments during the execution were collected, and all passengers were asked about their impression of the ride quality of the descent.

6.1.3 Flight execution

The flight from 07MT to KRNO took place as planned, testing the inflight NOTAM and Wx update capabilities of G2G, as well as an inflight re-routing to optimize the trajectory using the G2G application. It was already apparent before the return flight that only one descent into 07MT could be conducted due to aircraft availability. The routing of the flight was conducted as planned and illustrated in Figure 6.2. The captain of the flight was the pilot non-flying using G2G and the first officer was the pilot flying. After passing HILGR, the captain requested a CDA twice via G2G, and the trajectory request was successfully downlinked via data link. However, no trajectory could be calculated on ground because of a discrepancy of the expected and actual route input in the trajectory request [LL12]. As the aircraft was approaching the TOD location, it was decided to fall back on a prepared trajectory that was calculated before the flight with standard inputs and wind forecasts from the time of creation. Time and speed deviations occurred already at initialization of the guidance, as the planned point of the initialization differed from the actual point the guidance started[4]. This time deviation resulted in a slower than planned descent speed, which influenced the vertical profile demanding for speed brake deployment for a large part of the descent. Although this deviation also resulted in a larger amount of speed cues, fifteen during the entire descent, the captain of the ecoDemonstrator flight[5], decided to continue following the guidance below the planned limit of 10,000 ft AGL, all the way to the IAF MARJE in 5,000 ft AGL. The aircraft arrived at MARJE with minimal time and altitude deviations, stabilized for the approach.

6.1.4 Analysis

In a post-flight analysis, the performance of the system was determined and the pilot and passenger feedback was evaluated. Figure 6.4 depicts in five graphs the performance of the flight. From top to bottom, the relative altitude (black), planned altitude (gray), relative speed command (gray), and actual flown relative Indicated Airspeed (IAS) (black), as well as relative time, altitude, and speed deviation, are plotted over the distance from the start of the trajectory-following in per cent of their maximum value. The light gray shading indicates an active speed brake cue and the dark gray shading indicates an active vertical speed cue demanding a vertical speed of -700 ft/min. The relative time deviation plot shows a large initial time deviation, and it can be seen that the deviation is constantly decreased during the descent, being virtually zero by the time MARJE is reached and the

[4] Figure E.4 in Appendix E illustrates the request location of the pre-canned trajectory (INI4DT) and the location the aircrafts starts to follow the guidance at the beginning of the blue line.

[5] The Boeing chief test pilot, Captain Mike Carriker, was the Pilot in Command (PIC) of the flight.

guidance was no longer used. The effect of the vertical guidance cues on the altitude deviation can be seen in the plot. The large initial time deviation caused the flight to be performed slower than initially planned, leading to a negative speed deviation during the entire descent.

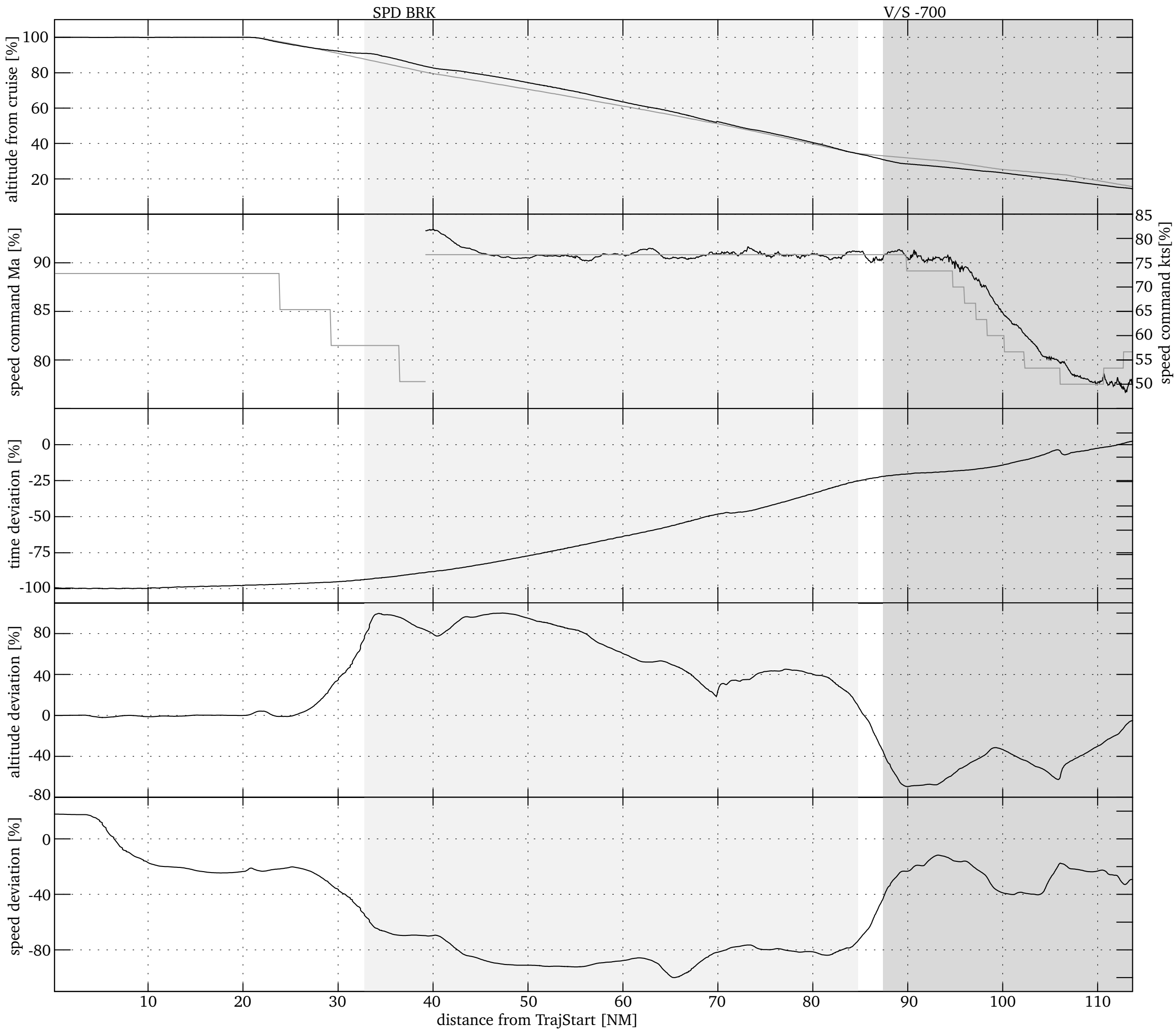


Figure 6.4.: Altitude, speed command and actual, and time, altitude, speed deviation for ecoDemonstrator flight in per cent of their maximum value (commanded (gray), actual (black))

For the set objectives the following analysis can be made:

Feasibility: The error in calculation of the trajectory on ground has shown how prone the system is to failure. Otherwise the system performed as expected from previous simulator trials, demonstrating the selection, negotiation, communication, and following of a continuous 4D trajectory.

Stability: The system always provided cues that were within the aircraft's operational envelope, resulting in a stable aircraft movement, even below the planned test environment of 10,000 ft AGL (compare Figure 6.4).

Robustness: The unplanned large initial deviations in time and speed have demonstrated the ability of the system to recover from such disturbances. In addition, the wind data from the prepared trajectory differed largely from the actual wind conditions during the descent. This had a negative impact on the aircraft performance but did not affect the robustness.

Accuracy: Due to the large initial time deviation, no evidence for the accuracy can be made from the test flight under nominal operational conditions with the calculation working. Although large deviations occurred at the beginning of the trajectory path, where deviations should be zero by definition, these deviations were minimized to zero seconds at the IAF (compare Figure 6.4). Previous simulator trials[6] indicate that performance within ±5 seconds time deviation and ±400 ft vertical deviation is feasible [LL12]. The performance is, however, highly dependent on accurate wind forecasts and also on the discretization steps and pilot performance in following the cues.

Ride quality: All but one passenger commented that the ride quality was acceptable or not different to a commercial flight [LL12]. It should be noted that the crew onboard the aircraft consisted of engineers and test pilots whose judgment of the ride quality might differ from the average airline customer. However, currently used autopilot modes (Vertical Navigation (VNAV) speed and vertical speed) were applied as inner control loop for the guidance, which limited the pitch and roll movements to degrees standard for today's commercial operations.

Usability: The fifteen speed advisory cues were caused by the guidance trying to minimize the time and speed deviations from the beginning of the trajectory path. Previous simulator trials have shown a smaller amount of speed cues. Although the number of speed cues was high during the descent, the captain of the flight continued to follow the guidance below the planned limit. This shows a high degree of confidence into the system. It should be noted that the acceptable workload of a task is higher on a test flight than in commercial aviation and that the flight experience of the Boeing chief test pilot exceeds the experience from the average commercial aircraft pilot. After previous training in the simulator, the pilot was able to generate a trajectory request and perform the actions indicated by the cues provided from the system.

[6] For a further analysis of previous simulator trials see Appendix E.1.1, Garrido-Lopez et al. [LL12] and Westphal [Wes10].

6.1.5 Discussion

A test flight into 07MT was conducted onboard the Boeing ecoDemonstrator. The CDA-MP trajectory management and guidance system was used in the G2G application. A trajectory request was successfully selected and downlinked, but an error occurred in the trajectory calculation software. It was decided to rely on a previously prepared trajectory which created large time and speed deviations at the beginning.

Besides the error in the trajectory generation, the test flight has demonstrated the feasibility to negotiate and communicate a continuous 4D descent trajectory using G2G on an EFB and evaluate the performance thereof. The guidance was stable and robust during the entire descent, allowing a further descent using the system beyond the planned test environment. The accuracy of the guidance cannot be judged from the flight due to large initial deviations in time and speed, but previous simulator trials have shown accurate trajectory following using CDA-MP. The ride quality was judged mostly positive as currently used autopilot modes were used.

The test flight can be seen as a successful demonstration of a 4D trajectory arrival guidance system. However the flight has also shown how prone such a system is to failure and a higher degree of robustness and redundancy is needed for the operational integration into commercial service.

6.2 DLR HETEREX flights

Within the German research project HETEREX a flight campaign was conducted with the DLR to test G2G as retrofit Trajectory Management System (TMS) in a full 4D[7] environment. The scenario for the flight centered around the Terminal Control Area (TCA) of Hannover-Langenhagen, Germany, ICAO-Code (EDDV) to evaluate the feasibility and usability of G2G as TMS and to measure efficiency gains with the utilization of new 4D trajectories and Required Navigation Performance (RNP) terminal procedures. A direct connection between AOC, EFB and FMS eased the implementation of new trajectories while inflight. The flights aimed on evaluating this capability of communicating, negotiating and following of a trajectory under real-world conditions. The feasibility of such a system was examined which is limited by only few technical challenges but also by legal aspects. In the following a detailed description of the scenario, the flight execution and results is given.

6.2.1 Objective

The objective of the DLR HETEREX flight trials was to evaluate the performance following a 4D trajectory and to demonstrate the operational feasibility, usability and performance

[7] Compare Section 2.2.2 for details on the assumptions of full 4D.

of a retrofit TMS connected to the aircraft's FMS in an automatic control integration under real-world conditions. In detail the following seven features of the G2G application were examined on their feasibility, usability and performance in operation.

Taxi Routing The taxi-routing feature was not the focus of the flight trial but was used to demonstrate efficient transitions from and to the airport runway.

Inflight updates NOTAM, Wx and flight plan updates were received and presented to the pilot to enhance the Situation Awareness (SA).

4D constraint editing To participate in the trajectory negotiation process, the editing of time constraints was evaluated.

PACeR depiction The usability of the Precision Aircraft Control enhancing Route (PACeR) was determined in a real flight under realistic wind conditions.

4D performance The feasibility to meet the entered time constraints was examined.

RNP procedures The predictability of the 4D performance was enhanced through the use of RNP procedures.

FMS connectivity The feasibility of passing routes and time constraints to the FMS was examined.

6.2.2 Scenario

A scenario was developed to support the evaluation of the seven developed features and to demonstrate efficiency gains in the EDDV TCA [PPM+12]. The flight campaign was divided into three test flights. Their routing and test procedure are presented in the following and an overview of the hardware integration is given.

Routing

The flight campaign was divided into three test flights in order to facilitate all test points and to generate sufficient data for the analysis. All flights were centered around the TCA of EDDV. The routing of the three flights is illustrated in Figure 6.5.

Flight 1: EDVE - EDDV DLE6T - (L980) ROBEG - BADMU - MOBSA - OSN - VIS1D

Flight 2: EDDV - (LBSF) - EDDV HETEREX RNP SID RWY 27L - (M852) HLZ - (L980) ATROS - DLE - ROBEG - BADMU - MOBSA - OSN - HETEREX RNP Approach RWY 27L

Flight 3: EDDV - EDVE POVE1F - POVE3R - RNAV RWY 26

The first flight would lead from Braunschweig-Wolfsburg, Germany, ICAO-Code (EDVE) to EDDV on standard terminal procedures to serve as reference and test the taxi routing on ground as well as an inflight NOTAM update. After another taxi test on the ground in EDDV the second flight would be planned and briefed. The initial routing was planned

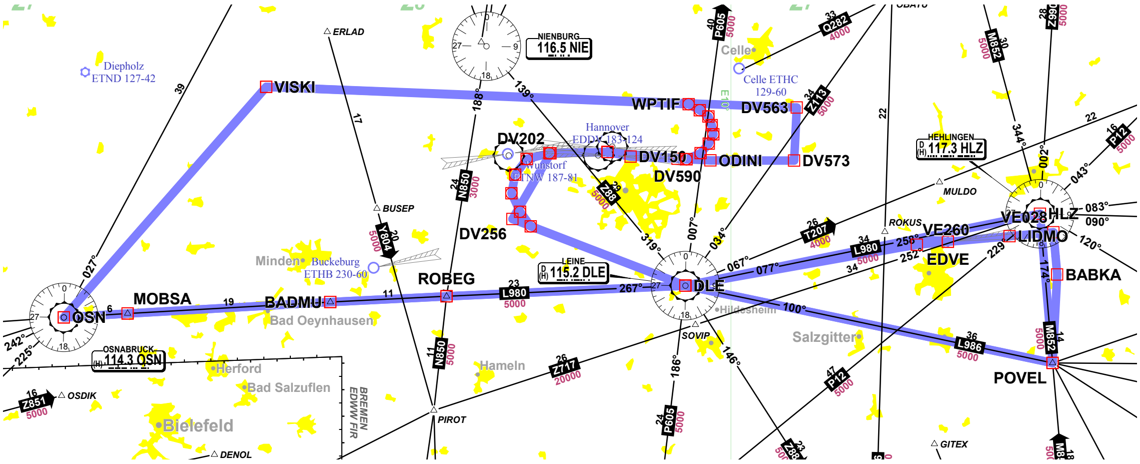


Figure 6.5.: Route for DLR HETEREX Flight EDVE-EDDV-EDVE created with JeppView [Jep13]

to lead from EDDV to Sofia, Bulgaria, ICAO-Code (LBSF). After take-off the flight would be re-routed, because of a fictional Notice to Airmen on volcanic ash activities (ASHTAM) over south-east Europe, to return to EDDV using the developed RNP approach procedure developed within HETEREX. The last flight from EDDV to EDVE would be a ferry flight on which G2G would be only used as paper chart replacement.

Test procedure

During the entire test flights, starting with the briefing in pre-flight and ending after reaching the final parking position, the research questions were tested. Not all of the seven features under evaluation were part of all of the three planned test flights.

On the first test flight the focus was on the taxi routing to be demonstrated in EDVE and EDDV, an inflight NOTAM update informing about a closure of Runway (Rwy) 27R and the FMS connectivity, to send the route received from the AOC to the FMS, as well as to depict the active Route from the FMS in G2G. The flight should also give baseline performance measurements for a post flight comparison of the Area Navigation (RNAV) and 4D RNP approach trajectories.

The second test flight was the central test flight of the campaign, aiming to demonstrate an RNP departure, inflight Wx update from the AOC as fictional ASHTAM preventing the continuation of the flight to LBSF and being resolved through an inflight re-routing requested from the pilot through G2G and implemented through the FMS connectivity. In addition 4D time constraints should be edited and implemented by the pilot at the waypoints OSN and VISKI. On the approach to EDDV an RNP approach procedure would be used to evaluate the efficiency gain through the use of Trajectory-Based Operations (TBO) and RNP over current operations.

On the last test flight none of the features besides the taxi routing were planned to be tested and the G2G application should serve as paper chart replacement only. All flights included the test of the usability of an initial route, NOTAM and Wx briefing and full paper chart replacement for all phases of flight.

Hardware integration

The ATRA was equipped with two Rockwell Collins class 2 EFB touchscreens and docking stations. These EFBs depicted in Figure 6.6(a) were driven by two Fujitsu Lifebooks P771 running Windows XP and hosting the G2G application. The laptop was connected with a network cable from the cockpit to a flight engineer computer in the cabin. Through this cable connection the aircraft data link and the DLR datapool could be accessed which stored the aircraft state data and served as interface to the DLR FMS. The DLR FMS was controlled from the flight engineer station in the cabin. The active trajectory as well as guidance was presented to the pilot flying on a foldable experimental display in front of the co-pilot seat as is illustrated in Figure 6.6(b). The captain as pilot non flying interacted with the EFB system and the first officer as pilot flying followed the flight director of the Primary Flight Display (PFD) presented on the foldable experimental display[8].

(a) Rockwell Collins EFB (red)

(b) Foldable experimental display

Figure 6.6.: Hardware integration in ATRA

Measurement

During the test flights all available performance data were collected onboard the aircraft. In addition to the performance data, system data was collected on the communication of the subsystems, for post flight analysis. To measure the usability of the system for

[8] A simplified architecture of the systems and the pilots interaction is depicted in Figure E.10 in Appendix E.2.

the pilots, subjective feedback was collected already in simulator sessions in the Generic Experimental Cockpit Simulator (GECO) preparing for the flights[9]. This feedback was complemented and enhanced by feedback collected during the flight from an observer and post flight questionnaires.

6.2.3 Flight execution

Due to adverse Wx conditions and technical difficulties in the integration, the flights were conducted in January 2013 over two non-consecutive days. At this time the visual minima allowed the flights only on few days. In addition, a high air pressure area caused stable East wind conditions which did not support the scenario that was laid out for West wind conditions.

In the last week in which the aircraft was available for the project, the decision was made to restructure the test plan in order to still be able to conduct most test points, under the given meteorological conditions. The program was divided into two parts. The first part consisted of standard terminal procedures to EDDV and back to EDVE under East wind conditions. This part enabled the test of the 4D functionality, inflight updates as well as the taxi routing functionality on ground in EDDV. For the second part the focus was on the RNP approach procedure to Rwy 27L and 4D functionality. This required Visual Meteorological Conditions (VMC) below Minimum Sector Altitude (MSA) and ideally West wind conditions or low traffic in EDDV that would permit approaches to Rwy 27L. The only initially planned test point that could not be tested with this new setup was the RNP departure procedure.

Day 1 Flight 1: EDVE - EDDV: DLE7U - (L980) ROBEG - BADMU - MOBSA - OSN - KUG1A

Flight 2: EDDV - (LBSF) - EDVE: POVE1Y - POVE3B - RNAV RWY 08

Day 2 Flight 3: EDVE - EDDV - EDDV - EDVE: DLE7U - (L980) ROBEG - BADMU - MOBSA - OSN - VIS1D -

EDDV - POVE1F - (M852) HLZ - (L980) ATROS - DLE - ROBEG - BADMU - MOBSA - OSN - HETEREX RNP Approach RWY 27L -

EDDV - POVE1F - POVE3B - RNAV RWY 08

The first part took place on January 23, 2013. On ground the pilot requested a briefing package in G2G from the AOC. This package included NOTAMs, Wx and the planned routing. The pilot reviewed the information selected terminal procedures and send the route from G2G to the DLR FMS. A taxi route to Rwy 08 was entered into G2G and followed. The pilot performed the take-off and followed the DLE7U Standard Instrument Departure (SID)[10]. After the aircraft was stabilized at cruising altitude in Flight Level (FL) 120 the pilot entered time constraints at BADMU and OSN. The pilot flying followed

9 Compare Appendix E.2.1 for details on the simulator trials in the GECO.

10 See Figure E.17 in Appendix E.2.2 for a chart of the SID.

the lower speed resulting from the time constraints. This was accomplished by guidance presented on the DLR FMS to the pilot flying on the foldable tray display as a flight director and speed cue on the PFD. After both time constraints were fulfilled a standard approach into EDDV on Rwy 09L was performed. On the ground the pilot used the G2G taxi guidance to taxi to parking stand 60. There all systems were reset with engines running and prepared for the next flight. The second flight was originally planned to LBSF. The briefing was retrieved using G2G as on the first flight. After taxiing to Rwy 09L and taking off on POVE1Y a Wx update was received from the AOC. It included a large fictional ASHTAM which prevented the further flight to LBSF. The pilot requested a re-routing to EDVE which was conducted with the base FMS of the aircraft using G2G as paper chart replacement only.

The second part of the HETEREX campaign took place on January 25, 2013. The main objective of this flight was to gather data to compare a 4D trajectory RNP approach into EDDV to the currently used RNAV transition. On that day East wind conditions were still present, but VMC below MSA were given. The flight therefore required a high degree of coordination with the Air Traffic Control Officer (ATCO) to be allowed to perform low approaches on Rwy 27L in EDDV. The runway was not cleared of snow that day, which made a landing impossible independent of the wind conditions. The flight took off from EDVE with the briefing and taxiing using G2G as on the previous flights. After taking off on DLE7U and climbing to the cruising altitude of FL120, a NOTAM update was received onboard the aircraft from the AOC. It included the fictional closure of Rwy 27R which did not affect the planned flight to Rwy 27L but was noted from the pilot to enhance the SA. The pilot performed a regular descent on the VIS1D transition. The vertical and speed profile was uninterrupted from the ATCO. The approach was conducted down to the decision altitude in 200 ft. A go-around procedure was performed by the pilot on the POVE1F SID. The new route was loaded into G2G, which led back to EDDV. It was reviewed and send to the DLR FMS for execution. Once the aircraft was stabilized again in FL120, the pilot entered time constraints at OSN and VISKI as time windows of ten seconds each. Both descent trajectories into EDDV are plotted in Figure 6.7 with the time constrained 4D trajectory RNP approach in black and the standard RNAV transition in gray. After another go-around in 200 ft G2G was used only as paper chart replacement on the return flight to EDVE.

6.2.4 Analysis

The analysis of the test flights can be subdivided into three parts. The analysis of the technical feasibility of the implemented system, the analysis of the performance following a 4D trajectory and the subjective pilot feedback on the usability of the application.

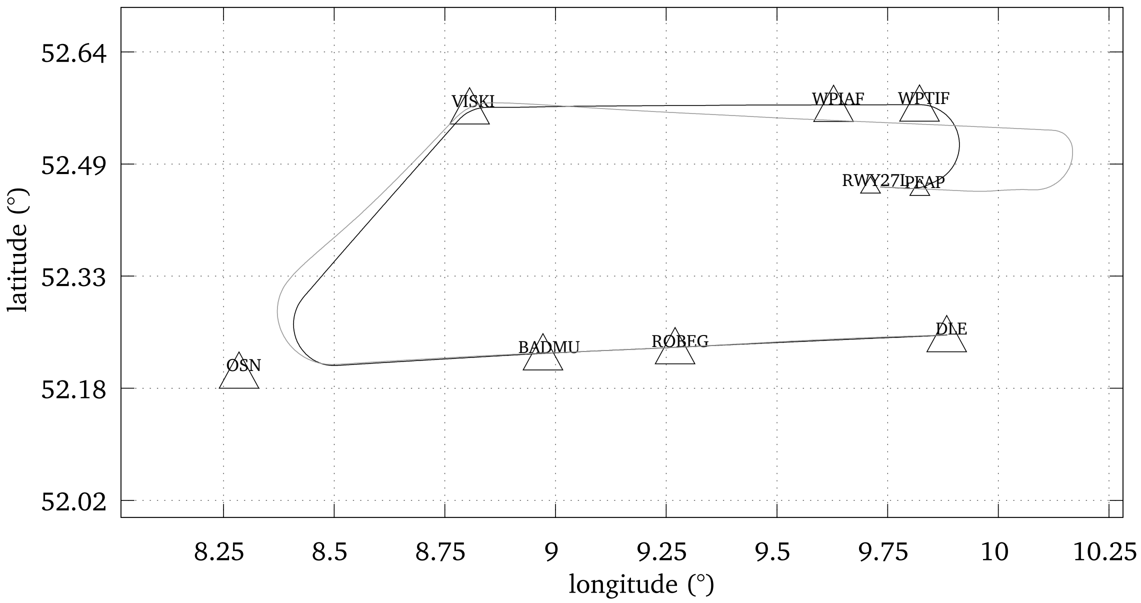


Figure 6.7.: Lateral profile for RNAV (gray) and RNP (black) approach into EDDV [GW13]

Feasibility

One of the objectives of the flight trials was to evaluate if an operational integration of the envisioned concept was feasible. The test flights could be conducted as planned, besides the limitations from the adverse weather situation, and completed with no technical difficulties. As the system was mostly based on hardware available to commercial aircraft today, challenges for an integration into service only derive from the data communication, FMS connectivity and depiction of an ownship during flight.

The integrated EFB system required a data link to communicate information with the AOC. Commercial data links are increasingly used in commercial aviation to connect the crew and the passengers with the internet during flight. Therefore data link availability is not assumed to be a limitation in the future, but rather available bandwidth. The benefits of the increased connectivity have to outweigh the costs of the data link for airlines. A direct connection with Air Traffic Control (ATC) over Controller-Pilot Data Link Communications (CPDLC) through the EFB is unlikely because of security concerns to connect a non DO-178C [Rad11] system to a critical flight system. However the Communication Management Unit (CMU) could provide read access to received CPDLC messages to the EFB for an graphical depiction of the proposed routing or constraints.

The connectivity from the EFB to the aircraft FMS was one of key test points of the flight trials. A direct connection would require the capability to load messages into the FMS either via emulation through an Aeronautical Radio Incorporated (ARINC) 758 CMU [Aer10a] or through an Aircraft Communications Addressing and Reporting System (ACARS) ARINC 724B management unit [Aer12c] both connected to the FMS via an ARINC 429 interface [Aer12a]. An alternative solution, which would look identical from a pilot workflow perspective, could be used to send the agreed trajectory as ACARS message from the AOC to the aircraft's FMS. This integration wouldn't require any further interfaces, than available today besides the EFB-AOC data link needed for all retrofit TMS applications.

Currently no ownship symbol may be presented on an EFB class 2 during flight[11]. For the PACeR depiction and tactical flight awareness, knowledge of the current position on the chart is needed. Therefore a revision of *Temporary Guidance Leaflet (TGL) 36* and *Advisory Circular (AC) 120-76B* [Eur04, Fed12a] is needed to support these operations. A similar process was followed to allow the depiction of an ownship symbol during taxi operations in an Airport Moving Map (AMM) on an EFB class 2[12].

Performance

To determine the performance and operational benefits from the use of 4D trajectories and RNP procedures, two arrivals were flown into EDDV. The first arrival was performed on the standard VIS1D RNAV transition and the second arrival was constrained by time constraints at OSN and VISKI waypoints delaying the flight approximately two minutes compared to the initial planning. From VISKI this arrival followed an RNP approach designed for the HETEREX flight trials. The RNP procedure consisted of an approximately 20 NM shorter route to the runway resulting in an about two minute shorter flight time given a nominal descent (compare Figure 6.7 for the flown lateral trajectories). Figure 6.8 illustrates the altitude profile for both flights plotted from VISKI. The RNAV approach was planned with a 3 NM level segment in 3000 ft for the Instrument Landing System (ILS) intercept. For the RNP approach a longer 5 NM level segment was planned in 5000 ft to ensure stable conditions before the continuous descent turn[13].

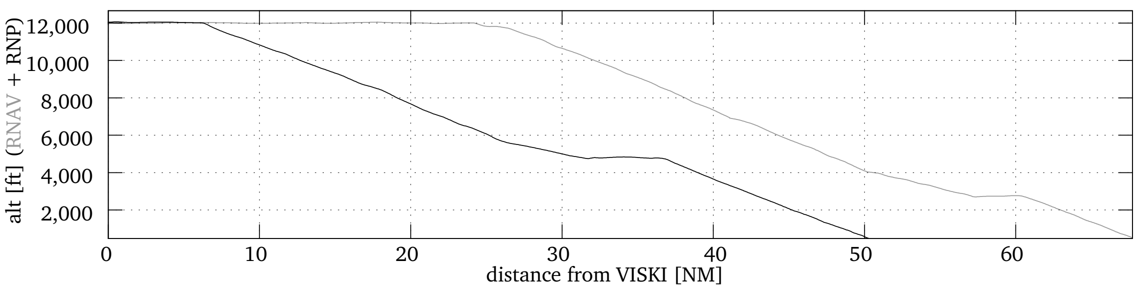


Figure 6.8.: Altitude profile for RNAV and RNP approach into EDDV [GW13]

[11] Compare to Section 2.5.

[12] *Technical Standard Order (TSO) C-165* defined the depiction of misleading information as a 'minor effect' and the failure of the complete system 'no effect' on the safety of the flight. This has led to *AC 20-59* permitting the depiction of an ownship symbol in an AMM during taxi operations on an EFB class 2 devices [Fed07a].

[13] See Figure E.15 in the Appendix for details on the designed RNP approach procedure.

For the RNP approach, time constraints were entered by the pilot to delay the arrival at OSN by one minute and at VISKI by two minutes compared to the initial planning. Both time constraints allowed a time window of ten seconds to pass the waypoint. From these constraints the temporal flexibility can be derived shown in the top graph in Figure 6.9. The slope of the straights is determined by the aircraft performance to increase or decrease speed relative to the planned speed profile[14].

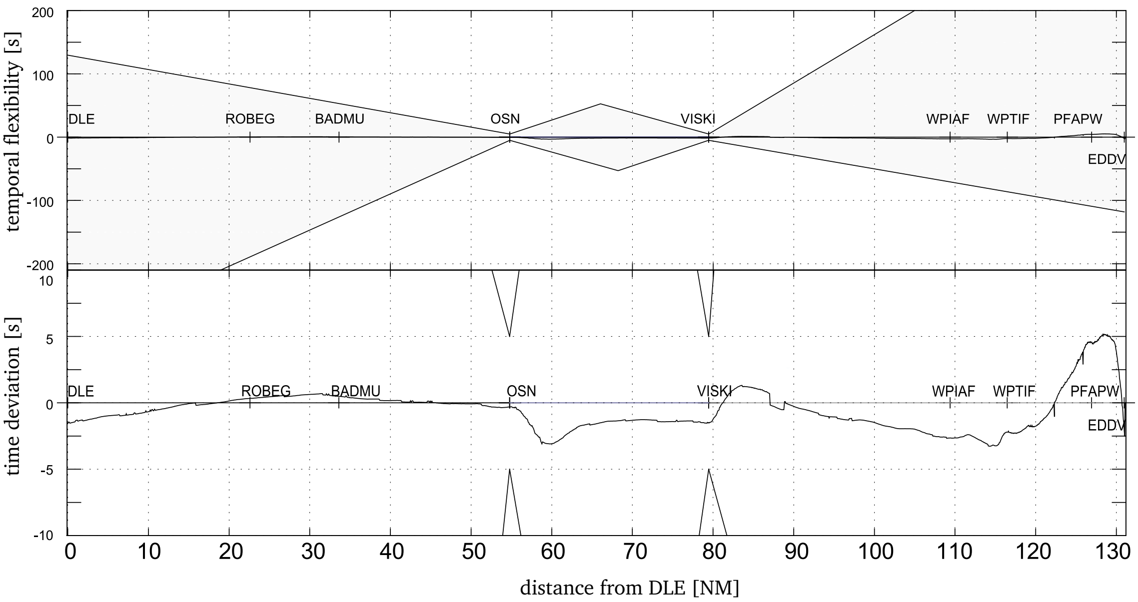


Figure 6.9.: Temporal flexibility and time deviation during RNP approach starting DLE [GW13]

The temporal performance of the flight is plotted in the lower graph in Figure 6.9. Although the speed had to be controlled by the pilot through a speed cue on the PFD, a high precision trajectory following was possible. Not only, were both time constraints at OSN and VISKI met, but the time deviation stayed within ±5 seconds during the entire approach. The large deviation on the final approach was the result of large deviations in the wind predictions[15].

The RNP approach required less fuel than the RNAV approach because of the shorter routing of the RNP approach and slower approach speed, because of the deceleration, resulting from the imposed time constraints. To quantify the fuel savings, an analysis was made to compare the fuel consumption and flight time of both approaches from waypoints along the trajectory[16]. For the waypoint VISKI the 4D RNP approach was two minutes and five seconds faster and consumed 38.4 kg less fuel which is a reduction of 22.6% for this segment of the flight. As the 4D RNP approach was decelerated already before reaching

[14] This slope is also used in the calculation of the PACeR algorithm.

[15] Strong winds of over 25 knots were encountered at low altitudes for both RNAV and RNP approach. Compare Figure E.13 in the Appendix.

[16] The results are listed in Table E.2 of Appendix E.2.2.

VISKI, the time difference for earlier waypoints was smaller between the two approaches but the absolute difference in fuel burn larger. For the first waypoint with comparable data ROBEG, the 4D RNP approach was fifty seconds faster as the time constraints were already active before reaching this waypoint and the 4D RNP approach used 57.6 kg less fuel compared to the RNAV approach a reduction of 15% for this segment.

Usability

The usability was determined by pilot remarks during the flight execution, and feedback provided in post flight questionnaires. As only two pilots operated G2G during the two flights and only three pilots in total were briefed in the simulator, no statistical analysis of the feedback was planned for[17]. The feedback on the usability can be differentiated between interface and operational usability [GW13].

Interface usability

The interface usability was inferior during the trial mainly for two reasons. The resistive touchscreen of the Rockwell Collins EFB did not accept input as pilots were used to from mobile phones or tablet computers with capacitive touchscreens[18]. This hardware deficiency was especially apparent when pan gestures were used as input. In addition the screen was rotated by ninety degrees as the G2G application was optimized to be used in portrait mode but the Rockwell Collins EFB could not be tilted.

Other difficulties the pilots had, using the application included the readability of, or interaction with, certain elements. Feedback was provided to improve the interface usability beyond the prototypical implementation. The detailed feedback to specific design elements is listed in the report on the flight trials [GW13].

In summary it can be noted, that the application was usable for the pilots as all tasks could be completed. However the discrepancies of the implementation due to the prototypical status of the application led to frustration by the user which focused a lot of feedback on these deficiencies.

Operational usability

The operational usability was determined by the degree G2G supported the pilot to fulfill the tasks of the given flight scenarios. It was remarked by the pilots, that the increased degree of integration with the AOC limits the flexibility of the application. For example, no terminal procedure can be previewed without editing the active route in G2G. This deficiency is due to the prototypical implementation of G2G focusing on an

[17] See Chapter 5 for a detailed human factors analysis of the TMS in the Technische Universität Darmstadt (TUD) research flight simulator.

[18] This issue was also experienced in the simulator sessions using a NavAero EFB (see Appendix E.2.1) but not during the ecoDemonstrator flight using the Apple iPad.

integrated scenario, but would have to be addressed for future development to support all operational conditions.

The pilots saw the PACeR depiction as a positive enhancement to increase their awareness of time constraints. The functionality to edit altitude, speed and time constraints within the G2G application was seen as redundant to already existing FMS functionalities and therefore rated as confusing if not misleading. For a briefing in pre-flight not all raw information of NOTAMs and Wx was available to the pilots but it was already filtered and processed. This was rated negatively by the pilots, as the filtering rules were not transparent[19].

6.2.5 Discussion

In the HETEREX flight trials the operational feasibility and usability of the realized retrofit TMS was evaluated. Adverse Wx prevented the execution of the original test plan. A revised test plan permitted to conduct all of the original test points except for a planned RNP departure. During the test flights, a taxi routing capability was tested to increase the predictability, of when the aircraft will reach the runway (before take-off) or gate (after landing). Inflight updates on Wx, NOTAMs and inflight re-routings increased the SA of the pilots and included the AOC mostly in the onboard decision making process. A 4D trajectory was created by the pilot through editing time constraints at waypoints which were then communicated to the FMS, followed and visualized using the PACeR depiction. A comparison of an RNP approach to a standard RNAV approach was conducted, demonstrating fuel and/or time savings (22.6% less fuel and 2 minutes 5 seconds faster using the RNP procedure) that can be realized with the utilization of 4D operations.

The analysis revealed that flights can be conducted as planned with G2G as retrofit TMS. The 4D performance of the flight showed only small time deviations although it was flown manually following flight director guidance on an experimental PFD. The usability was sufficient to fulfill all required tasks, however it led to frustration by the pilots because of the prototypical implementation.

The flights demonstrated the feasibility of a retrofit TMS to be integrated into current commercial cockpits. Further work is required in the standardization of the interfaces for communication from the TMS with AOC, ATC, and the FMS. However, an AOC and FMS integration with limited capabilities is feasible with today's avionics. In this integration the EFB would serve as strategic planning and negotiation tool with the AOC. For a product development, the system must be expanded to support the pilot in the execution of any operational scenario, and the user interface needs to be optimized to the deployment hardware.

[19] Compare the recommendations from Endsley et al. [EBJ03] on automation and filtering in Appendix A.4.

7 Conclusion and outlook

To conclude the thesis, the performed research is contemplated and an outlook on future work is given.

7.1 Conclusion

The increase in air traffic expected over the next years demands new technologies and procedures to provide sufficient capacity to accommodate it [Sta13a, Boe13]. The International Civil Aviation Organization (ICAO) states 4D Trajectory-Based Operations (TBO) as one means of improving traffic flows in high density air spaces [Int13b]. These improvements can only be realized when a large percentage of flights is equipped to support TBO [DPLM13]. To approach these challenges, the objective of this thesis was to realize a retrofit onboard Trajectory Management System (TMS) and to evaluate the realized system.

7.1.1 Foundation

A TMS needs to integrate into the existing highly complex Air Traffic Management (ATM) system. The current ATM system, as well as the expected changes in the future, were presented, and three generic trajectory descriptions discussed. The descriptions are differentiated by the number of time constraints (one vs. multiple) and the type of data (discrete vs. continuous). Besides the organizational integration into the ATM environment, a retrofit TMS needs to be integrated on today's Flight Deck. Therefore, the technologies of Flight Management Systems (FMSs), data link communication systems, and Electronic Flight Bags (EFBs) were discussed as considerations for the conceptualization of the TMS.

The TMS is envisioned as decision support system for the pilot. To design such system effectively, cognitive ergonomics were considered. At first, the functions of the TMS needed to be allocated between the computer and the pilot. This was followed by a human-centered design process describing how a usable design of the system could be achieved. The concept of Situation Awareness (SA) was introduced to serve as the process the pilot follows when taking a decision. The SA should, therefore, be supported by the TMS functionalities.

7.1.2 Realization

For the conceptualization of an onboard TMS, three tasks of the trajectory management were differentiated: negotiation, monitoring, and guidance. For the negotiation, the integration with different systems on the ground and onboard the aircraft was defined, and the graphical briefing of trajectories for the pilot was designed. To aid the pilot in the monitoring task of the trajectory conformance, the Precision Aircraft Control enhancing Route (PACeR) was conceptualized. The PACeR takes aircraft performance, economical and environmental constraints into consideration. From these constraints the PACeR presents an area in which the aircraft needs to stay to be able to fulfil the temporal constraints of the trajectory to the pilot. Four concepts of trajectory guidance were differentiated, focusing on different integrations with existing aircraft systems.

The conceptualized TMS was realized and evaluated. The JEPPESEN Gate-to-Gate (G2G) application was chosen, as it provided a seamless data driven chart that eased the integration of the conceptualized TMS. The TMS was integrated on four devices for varying setups differing in their hardware, system connectivity, and operational applicability. The realized integration could be evaluated in simulator trials and under real-world conditions in two flight trial campaigns.

7.1.3 Evaluation results

In simulator trials with seventeen pilots in the TECHNISCHE UNIVERSITÄT DARMSTADT (TUD) research flight simulator, the usability of the system was evaluated as well as the pilot's SA, workload, and performance when using the system. For the negotiation of a trajectory, the realized TMS showed a general usability; however, it received lower ratings compared to an integration into the aircraft FMS. The trajectory monitoring was also rated as usable. To evaluate the SA during the trajectory monitoring, the participants performed the task of identifying the next time constraint of the trajectory in a static flight situation to determine if they could meet the constraint in a timely manner. All pilots were able to successfully complete the task; however, the response times were significantly longer using the PACeR depiction in G2G compared to a textual constraint representation in the FMS. For the trajectory guidance, the participants were asked to adhere to time constraints at waypoints using the aircraft Flight Control Unit (FCU) with the lateral path flown in managed mode by the FMS. After a familiarization run, the pilots were asked to first meet a time constraint of $\pm$ 10 s and afterwards a constraint of $\pm$ 30 s. All pilots were able to adhere to both set time constraints.

The flight trials onboard the BOEING ecoDemonstrator and within the Heterogeneous complex air traffic (HETEREX) project have demonstrated the feasibility to apply the developed TMS under real-world conditions. The experiment onboard the ecoDemonstrator focused on the evaluation of a Human-in-the-Loop (HITL) 4D guidance based on the Continuous Descent Approach for Maximum Predictability (CDA-MP) principle with cues presented to the pilot in the TMS. The calculation of the reference trajectory on the ground failed and a trajectory prepared before the flight was used which led to large initial time and speed deviations. This failure showed how prone a 4D arrival guidance system is to errors which need to be mitigated. Besides the error in the trajectory calculation, a successful 4D Continuous Descent Approach (CDA) into the test airport Glasgow Industrial Airport, MT, ICAO-Code (07MT) was flown using the system.

The HETEREX flights aimed to evaluate the TMS in a full 4D TBO scenario from the departure gate to destination gate. The implemented TMS allowed the communication of trajectories from the Airline Operations Center (AOC), through the onboard TMS, to the aircraft's FMS. Inflight Weather (Wx) and Notice to Airmen (NOTAM) updates were demonstrated, which affected the planned trajectory requiring an inflight re-routing. At the departure and destination airport, the pilot was supported by taxi routing in G2G. Two arrivals were flown into Hannover-Langenhagen, Germany, ICAO-Code (EDDV), one being the standard Area Navigation (RNAV) transition to Runway (Rwy) 27L, and the second one a Required Navigation Performance (RNP) procedure designed for the project. The RNP approach was time-constrained at the entry waypoint to ensure an identical crossing time at the runway threshold for both approaches. The 4D constrained RNP approach used 22.6% less fuel on the approach because of the shorter routing. Additional savings could be realized through the slower speed on the 4D approach resulting from the time constraint. This resulted in a total saving of 15% compared to the RNAV approach with standard speeds during the entire arrival.

7.2 Outlook

Work remains in the implementation of services and applications and for further research to analyze and detail future TBO. The implementation of Initial 4D (I-4D) needs to be advanced to provide a basis for TBO, as well as to gather experience for future developments. Today's operations already provide a potential for the integration of TMS functionalities in order to assist in the mission management. Future research is needed to determine the benefits for an airline to invest into technologies allowing TBO from a network perspective. In the long term, the developed functions of the TMS need to be integrated into future cockpits natively.

7.2.1 Near-term implementations

With Single European Sky Air Traffic Management Research (SESAR) entering the deployment phase (2013-2020) [KK13, SES08, SES12] and Next Generation Air Transportation System (NextGen) in the implementation [Fed13a], the potential for implementations within the TBO environment arises.

Implementation of Initial 4D

Within the SESAR program, a series of test flights were performed with aircraft equipped to perform I-4D flights supported by an Air Traffic Control (ATC) ground side [Eur12a]. Beyond this first demonstration, the path to a widespread implementation into service is not yet laid out. The *SESAR ATM master plan* [SES12] states 2016 for the introduction of I-4D capable, with 2017 as milestone of an operational I-4D environment. From this milestone, it might take some time from the first integration into service to a widespread enabling of this technology onboard aircraft and on the ground.

Potential for trajectory based operations in today's environment

Even though the implementation of I-4D is still taking years, benefits can already be achieved today with the use of TBO. In the TUD research flight simulator evaluation pilots listed three cases where they are confronted with coordinated arrival times in today's environment. The entry into the North Atlantic Tracks (NAT) system, overflight times over Afghanistan coordinated by the Bay of Bengal Cooperative Air Traffic Flow Management System (BOBCAT) as well as a later or earlier arrival at airports to avoid a curfew.

These examples do not require an overflight coordinated within seconds but within minutes. A trajectory optimization application can aid the pilot in the execution to meet these objectives. The pilots mentioned that they avoid using the aircraft Required Time of Arrival (RTA) functionality, as it is perceived as applying aggressive control to meet the RTA, reducing fuel economy and passenger comfort. A strategic implementation of the guidance function providing the pilot a Cost Index (CI) with which the temporal constraint can be achieved might be sufficient and provide an added value for the pilot avoiding a manual iteration through the CI to optimize the overflight time.

7.2.2 Future research

Besides the direct product development for I-4D and pilot support systems, further research remains. The concept of the TMS can be expanded to allow full gate-to-gate support of the flight. The benefits of TBO need to be quantified for the specific scenario of an ATM stakeholder to analyze the profitability of an investment into these technologies and procedures.

Expansion of the concept

The taxi phase was not explicitly conceptualized within this thesis; however, the concepts for inflight trajectory negotiation, monitoring, and guidance can also be applied to permit 4D ground operations. The stakeholders differ for the ground application as the airport and ground handling agencies constrain the Target Windows (TWs) at the runway or at the gate. By expanding the overall concept, an application from the departure to the destination gate of a flight would be permitted.

Benefit analysis

Any investment of an Airline into technology has to either be mandated by regulation, or supported by a business case. To evaluate the investment into onboard TMSs, a holistic analysis of the optimization potential has to be performed for the use case of the evaluating airline. A fast time simulation of airline operations can aid to determine the optimization potential to be achieved with TBO and to decide which technological enablers need to be implemented in order to achieve these improvements.

The fast time simulation setup DE PRINS ET AL. at BOEING RESEARCH AND TECHNOLOGY EUROPE (BRTE) used to compare speed advisory, RTA, and CDA-MP arrival guidance methods [DPLM13] could be adapted to include the performance characteristics of a HITL integration of CDA-MP and time-controlled aircraft by an onboard retrofit TMS gathered in this thesis. This simulation can help in determining critical masses of equipage of the different 4D guidance systems, their benefits, and how they would operate under mixed traffic conditions.

Forward fit design

Today's Flight Decks are designed for today's operations. The development of a retrofit TMS solution can be seen simply as a cost-efficient interim solution until new Flight Deck designs support these functionalities natively. As the mission management objectives for the pilot change with the use of TBO, their workplace has to be designed to support these objectives. Emerging technologies enable new forms of interaction for the pilot with the Flight Deck to fulfill the tasks of the mission management. Therefore, research towards a new Flight Deck design that acknowleges the changed tasks of the pilot in the flight execution is recommended.

A Design considerations for onboard decision support systems

The Air Traffic Management (ATM) System of Systems (SoS) performance is the result of decisions taken by human operators [HKC+97]. To design a system for trajectory management, means to design a system for decision making. As the ATM system is too complex for a human operator to oversee, automation is needed to present the operator information relevant for decision making [WMPM98]. The Situation Awareness (SA) of an operator has a major influence on the decision making process. Therefore an analysis thereof is needed, as a system should be designed to increase the operators SA and at the same time limit the cognitive workload.

In the following concepts for function allocation, human-centered design, SA and mental workload are presented to be considered, in the conceptualization of an onboard decision support system for trajectory management. Errors caused by a missing SA can be categorized to the different Level of SA these causes are listed to keep in mind when trying to avoid SA errors. The concept of mental models such as SA stand not without criticism, this criticism is discussed to create an awareness of the limitations mental models adhere to. Following the concept of SA Endsley et al. provided a comprehensive list of fifty principles that were applied in this thesis wherever possible.

A.1 Function allocation

The question which tasks should be automatized by a machine and which tasks should be performed by a human operator has been first addressed in aviation by Fitts [Fit51], in 1951. His research resulted in the well-known Men Are Better At - Machines Are Better At (MABA-MABA) list shown in Table A.1. While some assumptions of the list may not be true anymore with the advancement of computers, Fitts started the foundation for today's field of function allocation research [dWD11].

Humans are still surpassing machines performance in terms of improvisation, judgment, and detection of unknown situations. Therefore, a Trajectory Management System (TMS) shall be designed as decision support system, presenting the operator information for monitoring and decision making, leaving the tasks that require fast simultaneous operations and repetition of tasks to the machine. However, the human operator needs to be aware of all performed tasks in case the operator needs to take over the tasks. Therefore, it is necessary to take a human-centered design approach that supports the operator's awareness of all required tasks and their execution.

Table A.1.: FITTS MABA-MABA list [Fit51]

Men Are Better At	Machines Are Better At
detection	speed
perception	power
judgment	computation
induction	replication
improvisation	simultaneous operations
long-term memory	short-term memory

A.1.1 Individual factors

ENDSLEY [End95] identified information processing mechanisms, mental models and automaticity as individual factors influencing the decision making process. These factors are influenced by prior experience and training as well as the operators' personal abilities. In addition, the operators' goals influence the SA and decision making by prioritizing information depending on the goal. These factors cannot be influenced directly by the system design, however, with knowledge of their underlying processes, the system design can optimize the representation of supporting information.

Working memory

The working memory influences the SA of an operator. Information can be stored temporarily in the working memory and combined with newly perceived information to update the mental picture of the evolving situation. Since the working memory is very limited, it can be one of the largest bottlenecks to SA according to FRACKER [Fra87].

Mental models

The mental models of an individual are stored in the long-term memory. Mental models are structures used to model system behaviors. The model helps the operator to understand a situation and to identify important information. A person without a good mental model of a system requires working memory to perform a task since understanding and projection is harder to achieve. Mental models can be rather complex for complex systems and schemes are developed to identify similar situations from experience and act according to these experiences. From these previous experiences people might develop a set of actions in response to a situation. These scripts lower the mental workload, do not require much of the working memory, and can lead to automaticity [RM85, EBJ03].

Automaticity

Actions are not only performed through the sequential process of acquiring SA followed by decision making, but some tasks are also performed as a direct response to a stimulus [JE00]. Automaticity can have both positive and negative effects on SA, as it frees mental capacity for more demanding tasks, but this routinized sequence of responses to a stimulus might not detect deviations to a standard situation that might be of importance. In aviation, checklists help to avoid automaticity and take all relevant information into account [EBJ03].

Goals

An individual performing a task is driven by a goal or objective to accomplish that task. When applying *top-down information processing* [Cas83], these goals determine the prioritization of essential elements. All actions are performed to meet the desired active goal unless a more important contradicting goal becomes active and the data is interpreted and prioritized in order to meet the new goal. A *bottom-up processing* of information may lead to a reprioritization of goals as information is perceived independent of the active goal. Both methods of information processing can be applied in parallel. This aspect can be used in system design to steer attention to a specific goal. The prioritization of multiple active and passive goals has a direct impact on the SA of an operator [EBJ03].

A.1.2 Task/System factors

The task and system with which the pilot interacts have a direct impact on the SA and decision making process. The performance can be optimized through a good interface design and correct allocation of system capabilities, while limiting the stress and workload induced by the automated system that keeps the pilot in the loop. The next section provides an overview of these factors.

System capabilities and interface design

The system capabilities and interface design depend on each other. The interface design is limited to the information the system can provide and the display information is limited by the interface. The system capabilities are limited to the system designer's understanding of what the system requires and what can be achieved with available technology [End95].

Both the system capabilities and the interface design have a direct influence on the operators' SA. Therefore, these are key when designing a system interacting with a human. Endsley et al. [EBJ03] propose Integrated Product Teams (IPTs) to work in concurrent engineering [PW89] and use an iterative spiral design process, illustrated in Figure A.1[1].

[1] This is a simplified version of the spiral model Boehm proposed for software development [Boe86].

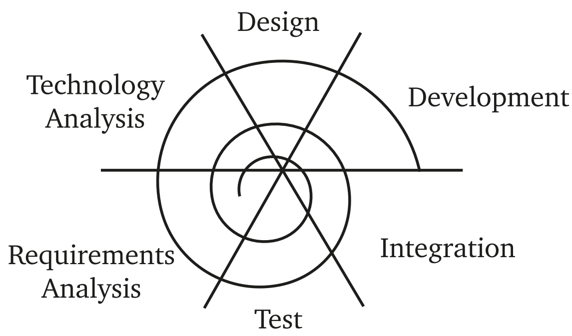


Figure A.1.: Spiral design process according to ENDSLEY ET AL. [EBJ03]

The process starts with a requirements and technology analysis for the tasks that the system should fulfill. This is followed by initial designs and their integration in the development for a first prototype. The prototype is integrated in the environment where it should be used and tested with human operators. Their feedback and performance measures are fed back into the requirements definition for the next iteration. This process is repeated until a system has evolved that satisfies the users' needs.

Stress and mental workload

Stress can come from various sources such as physical stress or social psychological stress. It can have positive and negative effects on performance. Limited stress can help to focus on relevant aspects of the situation; however, if the stress increases, it can lead to attention tunneling and limits the processed information [Hoc86, She81, End95].

As stress can lead to selective attention, so can an overload with too many tasks for the operator. Mental workload is introduced to determine the use of mental capacity. It relates the mental resource required to perform a task to the available mental capacity of the operator. EGGEMEIER ET AL. define mental workload as [EWKD91]:

> "*Mental workload refers to the portion of operator information processing capacity or resources that is actually required to meet system demands.*"

EGGEMEIER defines two regions of mental workload as is illustrated in Figure A.2. In the left region with the mental workload being lower than the available mental capacity, reaction times and errors remain on a constant level independent of changes in workload within this region. In the right region, where the operator is overloaded and mental workload exceeds the available capacity, the error rate and reaction time increases with the workload [Egg88]. GRIER ET AL. [GWK+08] refer to the threshold between both sides as "red line" of workload. As performance remains constant, with workload below mental capacity, objective measures for a change in workload are hard to apply when the operator is not overloaded.

WICKENS [Wic08a] developed the 4-D multiple resources model illustrated in Figure A.3, which differentiates between the: *stages of processing*, *codes of processing*, *modalities* and

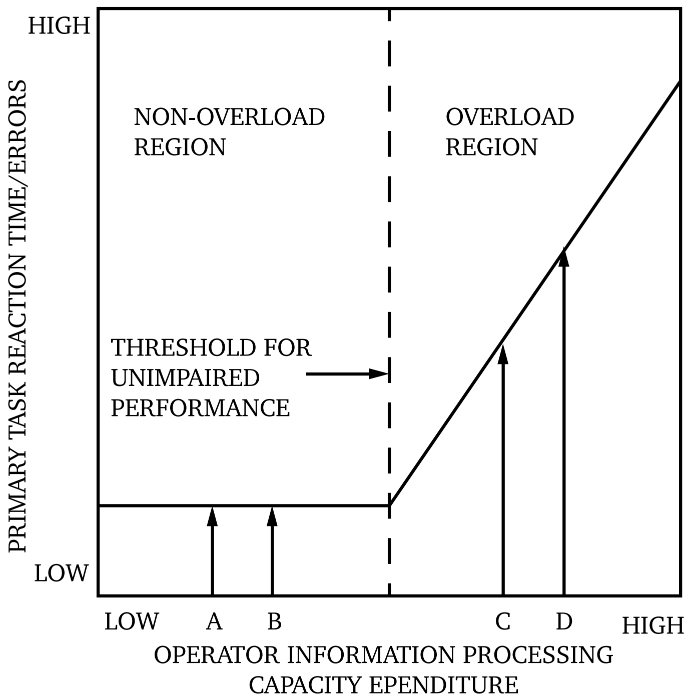


Figure A.2.: Relationship between mental workload and task performance after EGGEMEIER [Egg88]

later adding the *visual channels*. A capacity is assigned to each dimension for its use on time-shared tasks. The capacities of the dimensions are independent, as they are processed in different parts of the brain and ensure a neurophysiological separation of the resources.

ENDSLEY and DURSO state that loss of SA can occur at very high or very low mental workload [End93, DA10]. However, ENDSLEY [End95] also states that to achieve high SA with low workload is the ideal state. The loss of SA at low workload is caused by out-of-the-loop syndrome [EBJ03] because of a too-high degree of automation and a high system complexity.

Complexity and automation

Complexity can have a negative effect on SA because it either limits the operators' ability to comprehend and project information nor does it limit their ability to perceive information. ENDSLEY ET AL. differentiate three types of complexity [EBJ03]:

- **System complexity** is describing the overall complexity of the system and is dependent on four factors:
  - **Number of items** that are part of the system
  - **Degree of interaction** among the items of the system

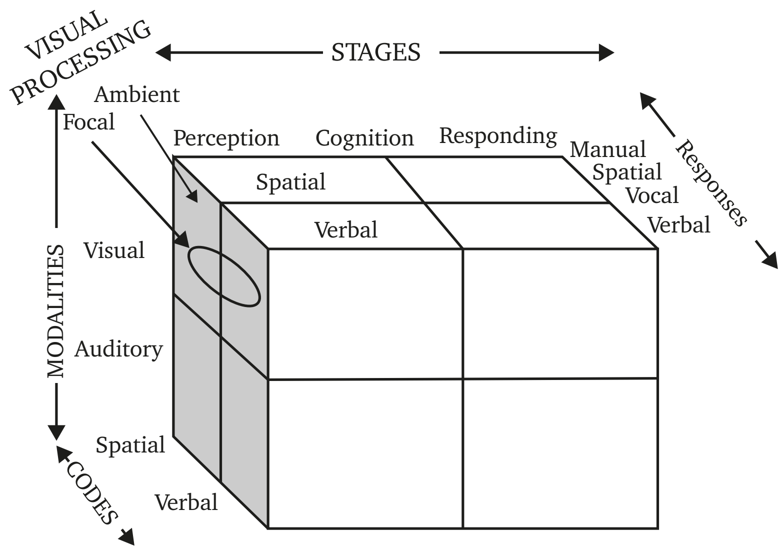


Figure A.3.: 4-D multiple resource model after WICKENS [Wic08a]

- **System dynamics** of the speed of the change of the system status
- **Predictability** of changes to the system state

- **Operational complexity** refers to the complexity that is imposed by the operational task to reach a certain goal. While systems might be rather complex, in respect to their internal processes, they do not have to be fully understood by the user, if a simplified mental model allows operation of the system with knowledge of all possible states that can occur.
- **Apparent complexity** is directly influenced by the interface design, as it relates to the representation of the system for the operator and can be subdivided into three groups:
  - **Cognitive complexity** depends on the logic applied by the system. It describes the difficulty to acquire a mental model of the system and apply system states to this model.
  - **Display complexity** refers to how information is exhibited to the operator. The density and layout has an influence on the complexity and should therefore be optimized.
  - **Task complexity** describes the responses of an operator to a system state to meet a desired goal. The complexity is dependent on how many steps need to be performed to meet the goal and how many goals are followed simultaneously as well as what are the interdependencies between the goals.

As complexity has a direct influence on the operator's SA and mental workload [End95], this should receive special attention in the system and interface design.

Where automation aims to reduce complexity, mental workload and errors caused by allocating tasks to a machine, rather than a human, realizes an undesired result. Automation (or the missing understanding thereof) has led to many fatal losses in aviation[2] and should, therefore, be applied carefully, and should be treated as learning experiences for making needed changes. Endsley and Kaber [EK99][3] identified four types of automation for a task:

- Monitoring
- Generating
- Selecting
- Implementing

If one of these functions is automated, the operator must increase the effort spent on monitoring the performance of the automation to detect errors. Endsley et al. [EBJ03] list three challenges for the successful integration of automation in a human-machine system:

Out-of-the-loop syndrome describes the decrease in operator's SA because of a lack of involvement in the task. In aviation, this characteristic is prevealent when automation degrades and the pilots need to perform manual control actions. As the pilots were not involved in the control task before the system degradation occurred, their SA of the task is limited [EBJ03, EY81, KW82]. To avoid this syndrome Endsley et al. [EBJ03] propose to automate tasks only when necessary, keeping the operator in control[4].

Mode awareness is the operator's lack of knowledge of the automation's current mode of operation. In today's automation systems, many automated systems are based on highly complex decision trees, which makes the decisions or modes of automation unclear for the operator. In addition to the complexity, poor interface design and inadequate training can foster the insufficient understanding of the system's behavior [WC80, Wic02, EBJ03].

Decision support dilemma characterizes the problem with relying on the decisions of an automated system. A decision support system or expert system will propose a solution to a situation, as presumably, the system has more information on the situation than the operator, but the selection of the solution is up to the operator. The problem is that either the operator will not rely on the recommended solution from the

[2] Endsley et al. [EBJ03] provide two examples: The first is the 1983 Korean Airlines flight that was shot down over Russian air space because of a falsely programmed Flight Management System (FMS) [Bil97, PMM96]. The second example is an American Airlines flight in 1996 that erroneously performed a Controlled Flight into Terrain (CFIT) because of an over reliance on automation from the flight crew [ES97].

[3] Similar: Parasuraman, Sheridan and Wickens [PSW00], or Billings [Bil97].

[4] See Appendix A.4 for the complete list of design principles proposed by Endsley et al.. [EBJ03]

system and also evaluate the situation leading to an increase in reaction time, or the operator will rely too highly on the proposed solution and follow the advice of the system even in cases where the automation proposes an erroneous [Sel90, EBJ03].

A.2 Errors in situation awareness

JONES and ENDSLEY created a taxonomy of SA errors according to their Level of SA [JE96]:

Level 1: Fail to perceive information or misperception of information
- Data not available
- Hard to discriminate or detect data
- Failure to monitor or observe data
- Misperception of data
- Memory Loss

Level 2: Improper integration or comprehension of information
- Lack of or incomplete mental model
- Use of incorrect mental model
- Over-reliance on default values
- Other

Level 3: Incorrect projection of future actions of the system
- Lack or incomplete mental model
- Overprojection of current trends
- Other

A.3 Criticism of mental models

The derivation of mental processes and description of the SA of a person is not an exact science. Models on the mental processes can be developed but they cannot be proven or rejected, as only inputs and outputs from the human are subject to experiments. Therefore the concept on SA and mental models as ENDSLEY defined it, is subject to criticism.

WICKENS [Wic08b] categorizes the criticism into two groups. The first group agrees, in general, with the concept on mental models and SA but disagrees in detail with measurement methods thereof. The second group doubts the validity of the overall concept and relies on performance indicators, such as *attention*, to determine the human performance in a system.

As examples for the first group, DURSO, RAWSON, and GIROTTO [DRG07] state criticism on the Situation Awareness Global Awareness Technique (SAGAT) method to measure SA developed by ENDSLEY [End88b], as it relies highly on cognitive memory. Instead DURSO ET AL. favor the Situation-Present Assessment Method (SPAM) [DD04] based on response time measurement.

The larger criticism of the cognitive approach to SA comes from DEKKER and WOODS [DW02], who criticized the simplification and validity of the MABA-MABA list for function allocation and their applicability to a generalized solution to determine the ideal degree of automation of a system. DEKKER and HOLLNAGEL [DH02] favor to focus on human-performance instead of what they call "folk models," referring to the larger cognitive construct of SA. They argue that the construct of SA is not decomposed into measurable functions, not proven by scientific measures and is overgeneralized. This criticism was replied to by PARASURAMAN, SHERIDAN and WICKENS, who provided a large empirical basis to support the validity of cognitive engineering constructs of ENDSLEY, ET AL. [PSW08].

Nonetheless, the cognitive model of SA as a dynamic decision making model described by ENDSLEY shall serve as guideline for the development of the TMS in this thesis.

A.4 Design principles

ENDSLEY proposes fifty design principles to meet the challenges of a user-centered design. These principles are listed below. Detailed descriptions of each principle is given in ENDSLEY'S ET AL. book *Designing for Situation Awareness: An approach to User Centered Design* [EBJ03]:

1. Organize information around goals.
2. Present Level 2 information directly - support comprehension.
3. Provide assistance for Level 3 SA projections.
4. Support global SA.
5. Support trade-offs between goal-driven and data-driven processing.
6. Make critical cues for schema activation salient.
7. Take advantage of parallel processing capabilities.
8. Use information filtering carefully.
9. Explicitly identify missing information.
10. Support sensor reliability assessment.
11. Use data salience in support of certainty.
12. Represent information timeliness.
13. Support assessment of confidence in composite data.
14. Support uncertainty management activities.
15. Just say no to feature creep - buck the trend.
16. Manage rampant featurism through prioritization and flexibility.
17. Insure logical consistency across modes and features.
18. Minimize logical branches.
19. Map system functions to the goals and mental modals of users.
20. Provide system transparency and observability.
21. Group information based on Level 2 and Level 3 SA requirements and goals.
22. Reduce display density, but don't sacrifice coherence.

23. Provide consistency and standardization on controls across different displays and systems.
24. Minimize task complexity.
25. Don't make people reliant on alarms - provide projection support.
26. Support alarm confidence activities.
27. Make alarms unambiguous.
28. Reduce false alarms, reduce false alarms, reduce false alarms.
29. Set missed alarm and false alarms trade-offs appropriately.
30. Use multiple modalities to alarm, but ensure they are consistent.
31. Minimize alarm disruptions to ongoing activities.
32. Support the assessment and diagnosis of multiple alarms.
33. Support the rapid development of global SA of systems in an alarm state.
34. Automate only if necessary.
35. Use automation for assistance in carrying out routine actions rather than higher level cognitive tasks.
36. Provide SA support rather than decisions.
37. Keep the operator in control and in the loop.
38. Avoid the proliferation of automation modes.
39. Make modes and system states salient.
40. Enforce automation consistency.
41. Avoid advanced queuing of tasks.
42. Avoid the use of information cueing.
43. Use methods of decision support that create human/system symbiosis.
44. Provide automation transparency.
45. Build a common picture to support team operations.
46. Avoid display overload in shared displays.
47. Provide flexibility to support shared SA across functions.
48. Support transmission of different comprehensions and projections across teams.
49. Limit non-standardization of display coding techniques.
50. Support transmission of SA within positions by making status of elements and states overt.

B Aircraft performance calculations

The calculation of the Precision Aircraft Control enhancing Route (PACeR) algorithm requires air speeds as inputs. This section explains the calculation of the minimum, and maximum speeds, determined by the envelope of the aircraft, as well as the calculation of the speed resulting from a Cost Index (CI), using the European Organisation for the Safety of Air Navigation (EUROCONTROL) Base of Aircraft Data (BADA) model for jet aircraft in cruise. With these speeds, both the flight envelope and economical part of the PACeR can be calculated. Where other literature is cited, the nomenclature was adapted to the BADA nomenclature.

B.1 Minimum speed

The minimum speed $V_{min,cr}$ is the lower flight envelope limitation at given environmental conditions. It is defined above 15,000 ft as in Equation B.1 [Eur12b]:

$$V_{min,cr} = MAX\left(V_{min,stall}, M_{bo}\right) \tag{B.1}$$

$V_{min,stall}$ can be calculated with Equation B.2, where V_{stall} is given by the BADA model.

$$V_{min,stall} = C_{V\,min} \cdot V_{stall} \tag{B.2a}$$

$$\text{with: } C_{V_{min}} = 1.3 \tag{B.2b}$$

At higher altitudes, the minimum speed is determined by the low speed buffeting onset limit, expressed as Mach number M_{bo}. The BADA model defines M_{bo} with a $0.2g$ margin in Equation B.3:

$$M_{bo}^3 - \frac{C_{Lbo(M=0)}}{k} \cdot M_{bo}^2 + \frac{mg}{S \cdot p \cdot k \cdot 0.583} = 0 \tag{B.3}$$

The cubic equation can be solved according to BADA [Eur12b] with the assistance of the values calculated in Equation B.4:

$$a_1 = -\frac{C_{Lbo(M=0)}}{k} \tag{B.4a}$$

$$a_3 = \frac{mg}{S \cdot p \cdot k \cdot 0.583} \tag{B.4b}$$

$$Q = -\frac{a_1^2}{9} \tag{B.4c}$$

$$R = \frac{-27 \cdot a_3 - 2 \cdot a_1^3}{54} \tag{B.4d}$$

Using trigonometry the three possible values for M_{bo} are listed in Equation B.5, where the lowest positive value defines the low speed buffeting limit M_{bo}.

$$X_1 = 2 \cdot \sqrt{-Q} \cdot \cos(\frac{\Theta}{3}) - \frac{a_1}{3} \tag{B.5a}$$

$$X_2 = 2 \cdot \sqrt{-Q} \cdot \cos(\frac{\Theta}{3} + 120°) - \frac{a_1}{3} \tag{B.5b}$$

$$X_3 = 2 \cdot \sqrt{-Q} \cdot \cos(\frac{\Theta}{3} + 240°) - \frac{a_1}{3} \tag{B.5c}$$

$$\text{with: } \cos\Theta = \frac{R}{\sqrt{-Q^3}} \tag{B.5d}$$

$$M_{bo} = MIN^{+}\left(X_1, X_2, X_3\right) \tag{B.5e}$$

B.2 Maximum speed

The maximum speed $V_{max,cr}$ is defined by either the V_{MO}/M_{MO}, which is a limit from the aircraft structure or $V_{maxthrust}$, which is the limit of the available thrust that in cruise is the most limiting factor for most commercial aircraft.

$$V_{max,cr} = MIN\left(V_{MO}, M_{MO}, V_{maxthrust}\right) \tag{B.6}$$

For the BADA model V_{MO} and M_{MO} are given for all available aircraft. $V_{maxthrust}$ can be calculated using Equation B.7.

$$THR_{max,cr} = C_{Tcr} \cdot C_{Tc,1} \cdot \left(1 - \frac{H_p}{C_{Tc,2}} + C_{Tc,3} \cdot H_p^2\right) \cdot \left(1 - C_{Tc,5} \cdot \left(\Delta T - C_{Tc,4}\right)\right) \tag{B.7}$$

$$D = THR = \frac{C_D \cdot \rho \cdot V^2 \cdot S}{2} \tag{B.8a}$$

$$\text{with: } C_D = C_{DO,CR} + C_{D2,CR} \cdot C_L^2 \tag{B.8b}$$

$$\text{with: } C_L = \frac{2mg}{\rho \cdot V^2 \cdot S} \tag{B.8c}$$

$$\text{results in: } THR = \frac{C_{D0} \cdot V^2 \cdot \rho \cdot S}{2} + \frac{2C_{D2} \cdot m^2 \cdot g^2}{V^2 \cdot \rho \cdot S} \tag{B.8d}$$

$$\text{reformatted: } 0 = V^4 - \frac{2 \cdot THR_{max,cr} \cdot V^2}{C_{D0} \cdot \rho \cdot S} + \frac{4C_{D2} \cdot m^2 \cdot g^2}{\rho^2 S^2 C_{D0}} \tag{B.8e}$$

This biquadratic formula can be solved by a change of variables of $V^2 = X$ using the pq-formula [BS81].

$$X_{1,2} = -\frac{p}{2} \pm \sqrt{(\frac{p}{2})^2 - q} \tag{B.9a}$$

$$\text{with: } p = -\frac{2THR_{max,cr}}{C_{D0} \cdot \rho \cdot S} \tag{B.9b}$$

$$\text{and: } q = \frac{4C_{D2} \cdot m^2 \cdot g^2}{\rho^2 \cdot S^2 \cdot C_{D0}} \tag{B.9c}$$

$$\text{results in: } V_{1/2/3/4,max} = \pm \sqrt{\frac{THR_{max,cr}}{C_{D0} \cdot \rho \cdot S} \pm \sqrt{\frac{THR^2_{max,cr}}{C^2_{D0} \cdot \rho^2 \cdot S^2} - \frac{4C_{D2} \cdot m^2 \cdot g^2}{\rho^2 \cdot S^2 \cdot C_{D0}}}} \tag{B.9d}$$

$$V_{maxthrust} = MAX\left(V_{1,max}, V_{2,max}, V_{3,max}, V_{4,max}\right) \tag{B.9e}$$

B.3 Speed from cost index

The economical PACeR depiction requires the resulting speed $V_{cr,CI} = V_{ECON}/M_{ECON}$ [Boe07, Air98] of a CI as input for the calculation. The resulting upper and lower speed boundaries of the CI are defined by V_{MRC} ($CI = 0$) and V_{max} ($CI = 999$). The speed and thrust for Maximum Range Cruise (MRC) conditions can be calculated with data for the minimum glide ratio ϵ_{min} according to Klingauf [Kli10].

$$f_{cr} = C_{f1} \cdot C_{fcr} \cdot THR \cdot \left(1 + \frac{V}{C_{f2}}\right) \tag{B.10a}$$

$$f_{cr,CI=999} = C_{f1} \cdot C_{fcr} \cdot THR_{max,cr} \cdot \left(1 + \frac{V_{maxthrust}}{C_{f2}}\right) \tag{B.10b}$$

$$f_{cr,CI=0} = C_{f1} \cdot C_{fcr} \cdot THR_{MRC} \cdot \left(1 + \frac{V_{MRC}}{C_{f2}}\right) \tag{B.10c}$$

$$\text{with: } THR_{MRC} = 2mg\sqrt{\frac{C_{D0}}{C_{D2}}} \tag{B.10d}$$

$$\text{and: } V_{MRC} = \sqrt{\frac{4}{3}\frac{mg}{\rho \cdot S \cdot \sqrt{\frac{C_{D0}}{C_{D2}}}}} \tag{B.10e}$$

(B.10f)

The calculation of a Minimum Cost Speed (ECON) speed V_{ECON} corresponding to a CI can be performed using the ECON Cruise Cost Function (ECCF) [PNM10, Sch08].

$$ECCF = \frac{CI + f_{cr,CI}}{V_{TAS} + V_{Wind}} \tag{B.11a}$$

$$V' = V_i | i \in N, V_i \in R, V_{min} \leq V_i \leq V_{max}, \frac{dECCF}{dV}(V_i) = 0 \tag{B.11b}$$

$$ECCF(V_k) = min\{ECCF(V_i) | V_i \in V'\} \tag{B.11c}$$

The calculation can be performed numerically, finding the minimum value of the ECCF with V_{min}/M_{min} and V_{max}/M_{max} as boundary conditions. The golden section search [GW04] provides the means of finding a minimum value numerically using Equation B.11 with the calculations of Equation B.10a and Equation B.8d for $f_{cr,CI}$ and $THR_{CI,cr}$ at given V', which is iterated until the minimum ECCF value has been found, resulting in $V_{ECON} = V_k$.

C Additional data on the realized trajectory management system

Supplementary to the information presented in Chapter 4, additional data and illustrations of the realized TMS are given in this Appendix. For the exchange of full 4D and continuous trajectories, a trajectory exchange model was developed and presented. The derivation of the constraint depiction used is described. Illustrations of the functionalities of the TMS integrated into Gate-to-Gate (G2G) are provided to assist in the understanding of the described functionality of Chapter 4. The arrival guidance bar[1] serves as an example, to create an understanding of how the design of the controls was derived.

C.1 Trajectory exchange model

The trajectory exchange model was originally developed to communicate the continuous trajectory and operational waypoints from the Airline Operations Center (AOC) to the aircraft. The modular setup, allows this to be used to communicate full 4D trajectories from the TMS to the DEUTSCHES ZENTRUM FÜR LUFT- UND RAUMFAHRT E.V. (DLR) FMS. It is comprised of a freetext definition of a continuous trajectory that can be adapted depending on the system that use it. In addition, the Extensible Markup Language (XML) schema defines information for Trajectory Change Points (TCPs)/waypoints at which constraints can be defined, see Figure C.1.

C.2 Functions integrated into Gate-to-Gate

The functions of the TMS described in Chapter 4 are depicted within G2G, to create an overview of their integration. Figure C.2(a) illustrates a descent using the arrival guidance system Continuous Descent Approach for Maximum Predictability (CDA-MP). In addition to the arrival guidance bar, operational waypoints are integrated into the chart by the "FL100" waypoint indicating when the descent through Flight Level (FL) 100 is planned, as is the same for the "FLAPS1" or "FLAPS5" waypoints. A time constraint is illustrated in Figure C.2(b) at the waypoint "OSN". The PACeR depiction is illustrated in Figure C.2(c) for the integration used in the Heterogeneous complex air traffic (HETEREX) trials with only the envelope PACeR depiction. The Constraint Editing System (CES) used by the pilot to alter constraints is shown in Figure C.2(d).

1 Compare to Section 4.5.2.

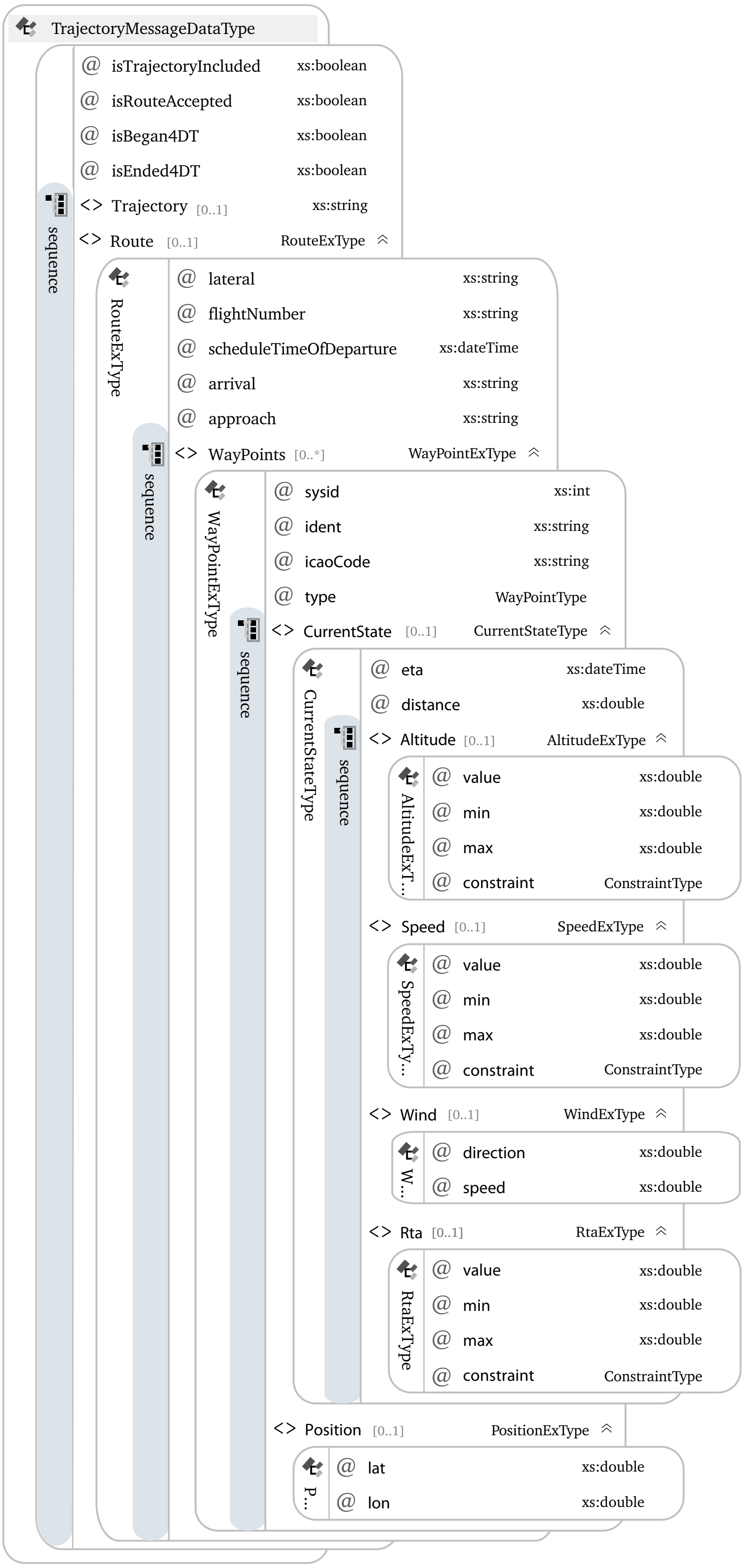


Figure C.1.: Trajectory exchange model

C.3 Constraint depiction

The recommended depiction of altitude from International Civil Aviation Organization (ICAO) Annex 4 (shown in Table C.1) was applied to all constraint types including time, altitude, and speed constraints.

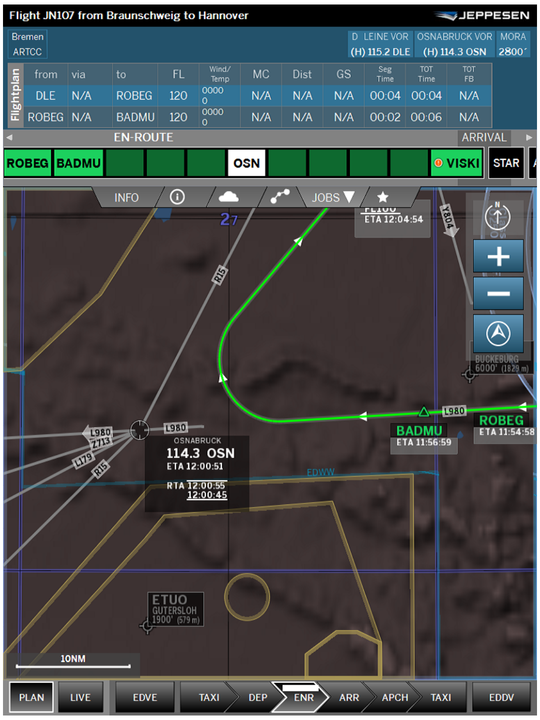
Table C.1.: ICAO Annex 4 altitude constraint specification [Int09]

125	Altitudes/flight levels	Altitude/flight level "window"	$\overline{\text{17 000}}$ $\underline{\text{10 000}}$	$\overline{\text{FL 220}}$ $\underline{\text{10 000}}$
		"At or above" altitude/flight level	$\underline{\text{7 000}}$	$\underline{\text{FL 70}}$
		"At or below" altitude/flight level	$\overline{\text{5 000}}$	$\overline{\text{FL 50}}$
		"Mandatory" altitude/flight level	$\overline{\underline{\text{3 000}}}$	$\overline{\underline{\text{FL 30}}}$
		"Recommended" procedure altitude/flight level	5 000	FL 50
		"Expected" altitude	Expect 5 000	Expect FL 50
	Note.– For use only on SID and STAR charts. Not intended for depiction of minimum obstacle clearance altitude.			

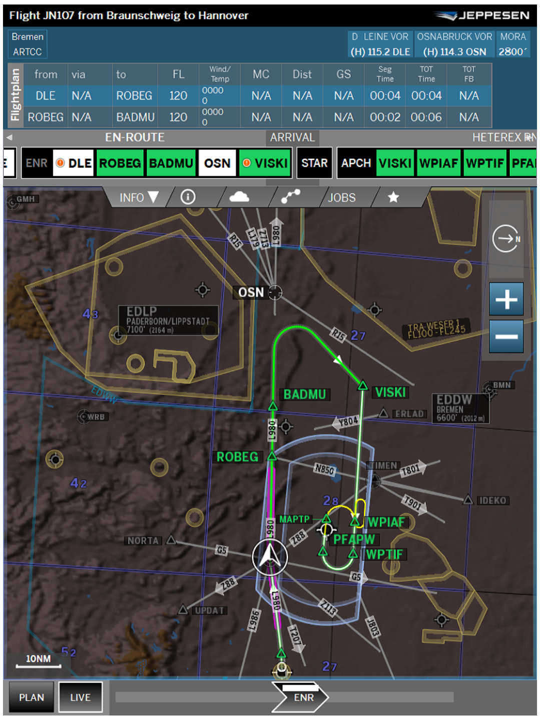
C.4 Evolution of the arrival guidance bar

As an example of how the iterative spiral design process detailed in Section 3.2.2 was applied, Figure C.3 illustrates the evolution of the arrival guidance bar integration in G2G. The first integration was developed as part of the author's diploma thesis [Wes10]. The pilot had to manually initiate the guidance at the Top of Descent (TOD) by pressing a button in the guidance bar, see Figure C.3(a). From this first integration the system was embedded into the operational architecture, described in Section 3.5.3, where the guidance started already in cruise once a trajectory was received from the AOC shown in Figure C.3(b). Besides this, the interface remained unchanged for the second iteration. With feedback from human factors experts and pilots it became obvious that the use of amber to indicate changed values was less than ideal as amber is used as a color indicating caution in Boeing avionics systems. To avoid confusion, amber was replaced with a blue matching the overall design of the G2G application as is shown in Figure C.3(c). With further feedback during simulator trials preparing for the ecoDemonstrator flight, it was determined that the inactive cues mislead the pilots to believe they were active cues. For this reason only two states remained in the final design, blue for a value that recently changed, and white for an active value, with non-active modes not being presented as is shown in Figure C.3(d). This example uses colors and elements depicted to show the sensitivity of the interface design in the environment of a modern flight deck.

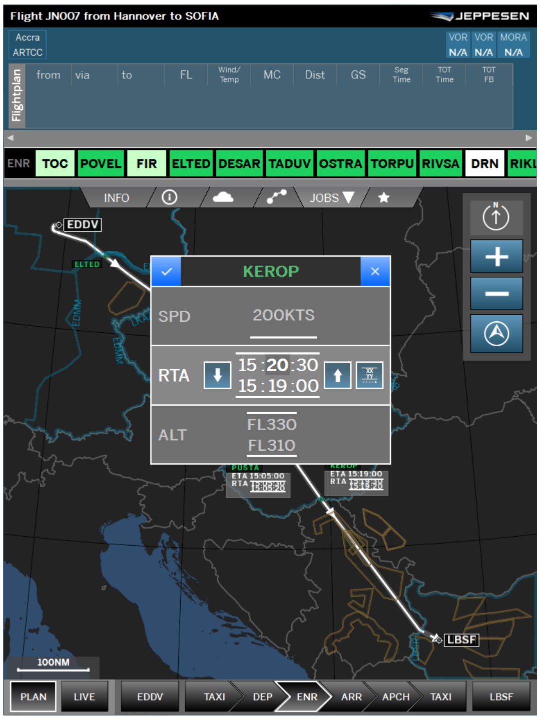
(a) Operational CDA-MP Waypoints ©Jeppesen



(b) Time constraint at "OSN" ©Jeppesen



(c) PACeR in Gate to Gate ©Jeppesen



(d) Constraint editing system ©Jeppesen

Figure C.2.: Features integrated into Jeppesen's Gate to Gate application

(a) First design [Wes10]

(b) Second iteration

(c) Third iteration

(d) Final design

Figure C.3.: Evolution of the arrival guidance bar

D Simulator evaluation data

The underlying data of the Technische Universität Darmstadt (TUD) research flight simulator trials is listed in the following Section.

D.1 Participants

The list of participants for the simulator trials is provided in Table D.1. The plus or minus in brackets indicates whether or not the next time constraint could be fulfilled (+) or not (-).

Table D.1.: List of participants

#	Airline	Rank	Flight hours	Type rating	Age	Sex	EFB	RTA	System 1	System 2
1	DLH	CPT	5,000	A320	38	M	✓	✓	FMS (+)	G2G (-)
2	DLH	CPT	12,000	A330/340	51	M	✓	✓	FMS (-)	G2G (+)
3	DLH	FO	5,000	B737	32	M	✓		FMS (+)	G2G (-)
4	DLH	CPT	16,000	EMB190	52	M	✓		FMS (+)	G2G (-)
5	DLH	CPT	10,500	A320	37	M	✓	✓	FMS (+)	G2G (-)
6	DLH	FO	4,800	A320	34	M	✓	✓	FMS (-)	G2G (+)
7	DLH	SFO	6,000	A380	34	M	✓	✓	FMS (+)	G2G (-)
8	DLH	FO	1,600	A320	25	M	✓	✓	G2G (+)	FMS (-)
9	DLH	CPT	21,000	B747	61	M	✓	✓	G2G (+)	FMS (-)
10	DLH	SFO	10,500	A330/340	42	M	✓	✓	G2G (-)	FMS (+)
11	DLH	FO	1,200	A320	32	M	✓		G2G (+)	FMS (-)
12	DLH	CPT	12,500	A320	43	M	✓		G2G (-)	FMS (+)
13	DLH	CPT	13,000	A320	47	M	✓	✓	G2G (+)	FMS (-)
14	DLH	CPT	17,000	A380	50	M	✓		G2G (+)	FMS (-)
15	AB	FO	4,500	B737	31	M	✓		G2G (-)	FMS (+)
16	DLH	CPT	17,000	B747	66	M		✓	FMS (-)	G2G (+)
17	/	FO	160	/	25	M			FMS (+)	G2G (-)

D.2 Modified MCDU pages

The vasFMC FMS was modified to allow the integration of full 4D trajectories into the FMS. Figure D.1 shows the changes to the FPLN and LATREV pages, which include "**between**" time constraints.

(a) FPLN page on ground (b) FPLN page airborne

(c) LATREV page on ground (d) LATREV page airborne

Figure D.1.: Time constraints integrated into MCDU pages

D.3 Additional analysis data

Additional data is provided for the analysis of the three domains of the TMS: negotiation, monitoring, guidance, and general feedback.

D.3.1 Negotiation

The following Section provides additional data on the usability, ratings, and open feedback is provided.

Usability

The System Usability Scale (SUS) can be examined in the ten underlying questions. Figure D.2 shows a box plot for the answers of both systems to these questions. The results of a Mann-Whitney test on their statistical is provided in Table D.2.

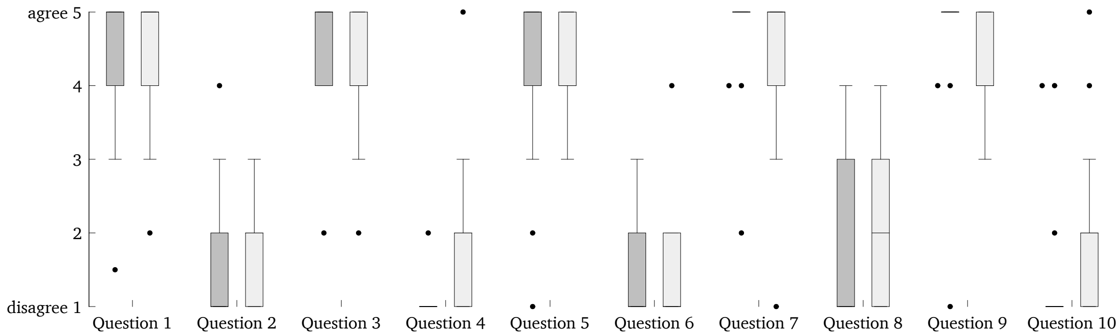


Figure D.2.: SUS Questions for FMS (black) and G2G (gray)

Table D.2.: Mann-Whitney test statistics for SUS ratings

	Question 1	Question 2	Question 3	Question 4	Question 5
Mann-Whitney U	133.5	120.5	99.5	67.5	112.5
Wilcoxon-W	286.5	273.5	252.5	220.5	265.5
Z	-0.424	-0.890	-1.712	-3.221	-1.202
FMS mean / SD	4.26 / 1.00	1.71 / 0.99	4.53 / 0.80	1.06 / 0.24	4.29 / 1.21
G2G mean / SD	4.41 / 0.87	1.88 / 0.78	4.12 / 0.86	1.79 / 1.02	4.18 / 0.73
Asymp Sig. (2-tailed)	0.672	0.373	0.087	**0.001**	0.229
	Question 6	Question 7	Question 8	Question 9	Question 10
Mann-Whitney U	128.0	103.0	141.0	72.0	75.5
Wilcoxon-W	281.0	256.0	294.0	225.0	228.5
Z	-0.677	-1.736	-0.130	-2.824	-2.657
FMS mean / SD	1.35 / 0.61	4.71 / 0.77	1.88 / 1.11	4.65 / 1.00	1.41 / 1.00
G2G mean / SD	1.53 / 0.80	4.29 / 1.05	1.88 / 0.99	4.18 / 0.64	2.06 / 1.09
Asymp Sig. (2-tailed)	0.498	0.083	0.896	**0.005**	**0.008**

Ratings

The ratings are divided into three categories of general ratings, task specific briefing questions and task specific questions to the static flight scenario.

General ratings

The following five questions were rated by the participants on a five-point LIKERT scale for both the FMS and G2G system:

1. The control of the system was self-evident.
2. Icons and Buttons were designed so that you could predict where they lead. (Cloud -> Weather, etc.)
3. The necessary professional jargon was observed.
4. Known Icons/Buttons were used similar to other programs. (e.g.: Clr = Delete, etc.)
5. The user interface was designed consistent according to a uniform pattern.

The results are shown in Figure D.3 as box plots. A Mann-Whitney test was used to identify significant differences in the responses for the two examined systems. The results and descriptive statistics of the test are provided in Table D.3.

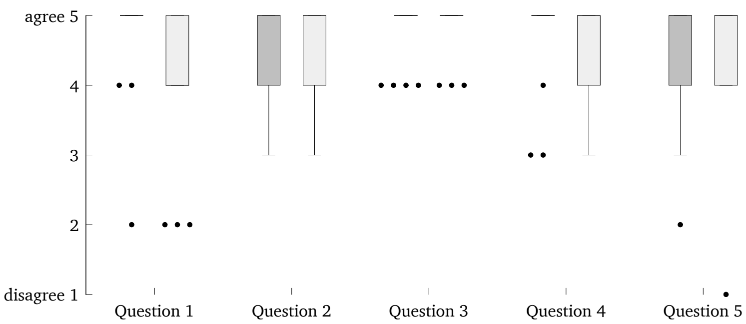


Figure D.3.: General ratings for FMS (black) and G2G (gray)

Table D.3.: Mann-Whitney test statistics for general ratings

	Question 1	Question 2	Question 3	Question 4	Question 5
Mann-Whitney U	93.5	135.5	136.0	108.5	142.5
Wilcoxon-W	246.5	278.5	289.0	261.5	295.5
Z	-2.077	-0.442	-0.418	-1.507	-0.082
FMS mean / SD	4.71 / 0.77	4.50 / 0.79	4.76 / 0.44	4.71 / 0.69	4.47 / 0.87
G2G mean / SD	4.12 / 1.11	4.41 / 0.80	4.82 / 0.39	4.47 / 0.62	4.47 / 1.01
Asymp Sig. (2-tailed)	**0.038**	0.721	0.676	0.132	0.935

Task specific briefing ratings

For the briefing task the first seven of the following eight statements were rated by the participants:

1. I was adequately supported during the execution of the task.
2. Necessary information was shown appropriately.
3. I needed assistance in solving the task.
4. I could hide unnecessary information.
5. I could show additional needed information.
6. I could modify shown information in their detail as I needed.
7. I could cancel wrong petitions or clicks after I noticed them.
8. I could easily determine whether I was too early or too late when I could not adhere to the time constraint.

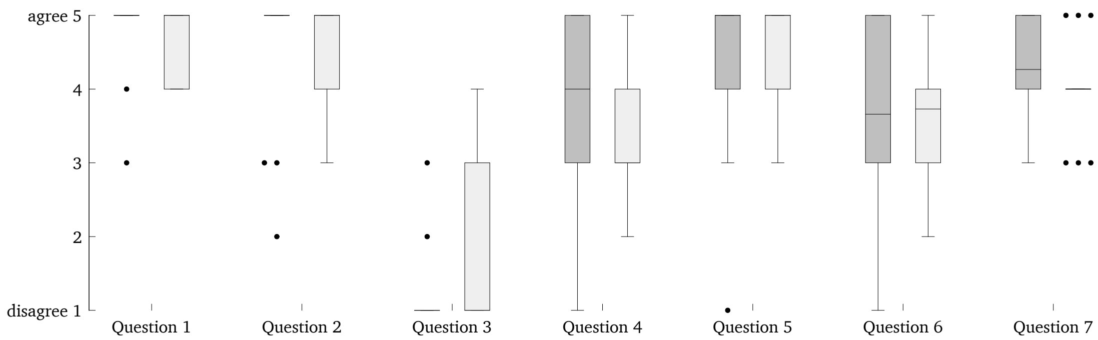


Figure D.4.: Task specific ratings briefing for FMS (black) and G2G (gray)

The results are shown in Figure D.4 as box plots. A Mann-Whitney test was used to identify significant differences in the responses for the two examined systems. The results of the test and descriptive statistics are provided in Table D.4.

Table D.4.: Mann-Whitney test statistics for briefing questions

	Question 1	Question 2	Question 3	Question 4
Mann-Whitney U	113.5	112.0	91.0	142.5
Wilcoxon-W	266.5	245.0	244.0	295.5
Z	-1.447	-1.200	-2.293	-0.071
FMS mean / SD	4.61 / 1.01	4.50 / 0.96	1.39 / 1.01	3.61 / 1.60
G2G mean / SD	4.50 / 0.76	4.41 / 0.69	2.17 / 1.46	3.78 / 1.36
Asymp Sig. (2-tailed)	0.148	0.230	**0.022**	0.943

	Question 5	Question 6	Question 7	
Mann-Whitney U	143.0	112.5	83.0	
Wilcoxon-W	296.0	232.5	188.0	
Z	-0.058	0.0	-1.035	
FMS mean / SD	4.56 / 1.50	4.13 / 2.12	4.25 / 2.19	
G2G mean / SD	4.72 / 1.48	4.25 / 2.19	4.67 / 2.57	
Asymp Sig. (2-tailed)	0.953	1.0	0.301	

Task specific static flight ratings

For the static flight scenario the participants rated the eight statements above for both systems. Figure D.5 depicts the results as box plots for both systems. A Mann-Whitney test was used to identify significant differences in the responses for the two examined systems. The results of the test and descriptive statistics are provided in Table D.5.

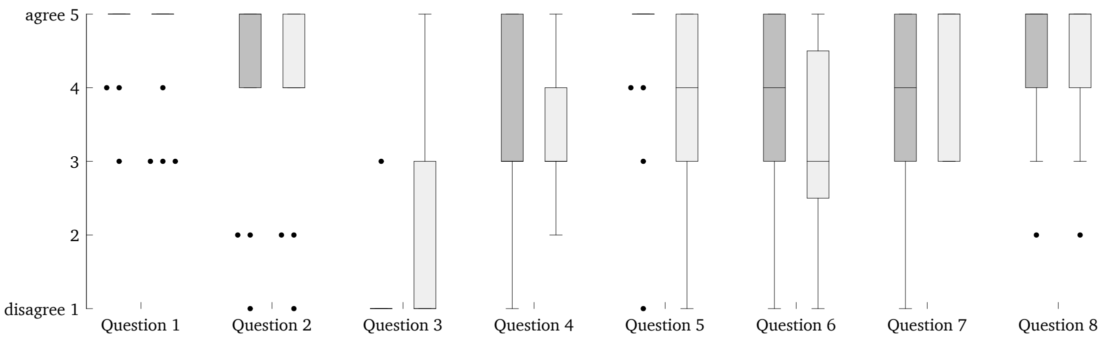


Figure D.5.: Task specific ratings static flight for FMS (black) and G2G (gray)

Table D.5.: Mann-Whitney test statistics for static flight

	Question 1	Question 2	Question 3	Question 4
Mann-Whitney U	133.5	116.5	85.0	125.0
Wilcoxon-W	286.5	269.5	238.0	261.0
Z	-0.537	-1.090	-2.643	0.119
FMS mean / SD	4.76 / 0.55	4.29 / 1.27	1.12 / 0.47	3.31 / 1.36
G2G mean / SD	4.59 / 0.77	4.06 / 1.21	2.00 / 1.28	3.44 / 0.87
Asymp Sig. (2-tailed)	0.708	0.339	**0.041**	0.926

	Question 5	Question 6	Question 7	Question 8
Mann-Whitney U	102.0	100.0	84.5	129.5
Wilcoxon-W	255.0	253.0	204.5	282.5
Z	-1.622	-1.074	-0.650	-0.588
FMS mean / SD	4.41 / 1.09	3.80 / 1.33	3.80 / 1.38	4.47 / 0.85
G2G mean / SD	3.82 / 1.29	3.29 / 1.36	4.25 / 0.86	4.35 / 0.84
Asymp Sig. (2-tailed)	0.150	0.313	0.555	0.610

Open feedback

In addition to the ratings provided in the SUS and Likert scale, the participants provided open feedback to the tasks they performed.

Participant feedback to MCDU

- MCDU adaption good, information is where you look for it
- RTA window very short (20 s)
- ETA cannot be defined manually on ground (mentioned twice)

- Working with the MCDU for more than 15 years made this task very easy to solve
- The MCDU system seems basic without much visualization, but displays relevant data effectively
- Known color coding of constraints, no additional training -> good
- Add ± offset to the mean displayed e.g. 14:33 +- 2 min
- Position of the ETA could move depending whether or not the constraint is met.
- Additional button on the MCDU to depict the next constraint waypoint could help (mentioned twice)
- Would be helpful to mark waypoints with time constraint in the navigation display. I have to calculate manually where I am relative to the constraint, not good for situation awareness.
- Difficult to read, asterix hard to see (mentioned four times)

Participant feedback to G2G

- Depiction of the constraint should be differentiated by color, when out of pacer the color of the "area to be in" should be amber or magenta according to "constraint not fulfilled" (mentioned five times)
- Since there is no option to enter the departure time it is difficult to estimate the eta's of the required waypoints (mentioned twice)
- Hiding unnecessary information could reduce workload by focusing only on important criteria (mentioned five times)
- Constraint label not visible when zooming in (mentioned twice)
- I am confident that after a little bit of practice with this "new" system, using it properly should be not a problem
- Provided all software functions work properly (e.g. correct display of relevant waypoints at all zoom levels/map scales)

D.3.2 Monitoring

For the monitoring part of the trials, histograms are provided in Figure D.6 for the LIKERT scale ratings, and the open feedback is listed in the following:

- Color depiction not optimal (mentioned four times)
- Wider magenta line, especially the envelope part
- The monitoring scale should always be visible, regardless of zoom level or map position displayed
- A feature to show the minimum and maximum calculated speeds for both envelopes would be helpful. However, this information does not need to be displayed constantly
- Integration: I would appreciate if this type of display would be integrated on both a ND and an EFB
- It should be evaluated if the information for monitoring is not already done by existing hard/software - FMC with RTA-MODE
- The monitoring system provides "interesting" information; however, this information is also available from other existing sources/instruments on the flight deck. The question remains whether it is necessary or helpful to supply the information again via the monitoring system. My personal opinion on this is that it is not necessary.

D.3.3 Guidance

For the guidance part of the trials, histograms are provided in Figure D.7 for the LIKERT scale questions and the open feedback is listed in the following:

- Same font size ETA and RTA (mentioned twice)
- Time constraint management in operational environment much more demanding
- Used colors arguable (mentioned three times)
- Recommended speed: displayed in red with arrow up or down if deviating from current speed. Best with different shadings of red depending on the deviation to the current speed (mentioned three times)
- Good information would be the mileage to fly from present position to the constraint waypoint (since pilots often calculate GS/60=x [NM/min] -> Dist/x=t[min] (mentioned twice)
- The information in the guidance bar and the monitoring scale on the map should be presented together, not as divided as they are now
- I am missing a fuel display, meaning the effect a higher speed has on the fuel consumption

D.3.4 General

To contemplate on the trials, histograms are provided in Figure D.8 for the LIKERT scale questions and the open feedback is listed in the following:

- Manual speed selection after passing a waypoint workload intensive
- Icons should differentiate more depending on times they are used
- The constraint window display should be bigger and thus easier to read. The fonts used are too small in my point of view. A UTC clock should also be displayed in order to better evaluate the situation to meet the time constraint. (mentioned three times)
- Good overview depiction of the entire route with time constraints
- List time constrained waypoints in briefing package textual
- All in all very interesting outlook onto future concept of air traffic management solutions, however I think it is important to factor in potential operational issues/limitations during development. (for example speed restrictions by the presence of turbulence or technical issues which could limit the speed of the aircraft.)

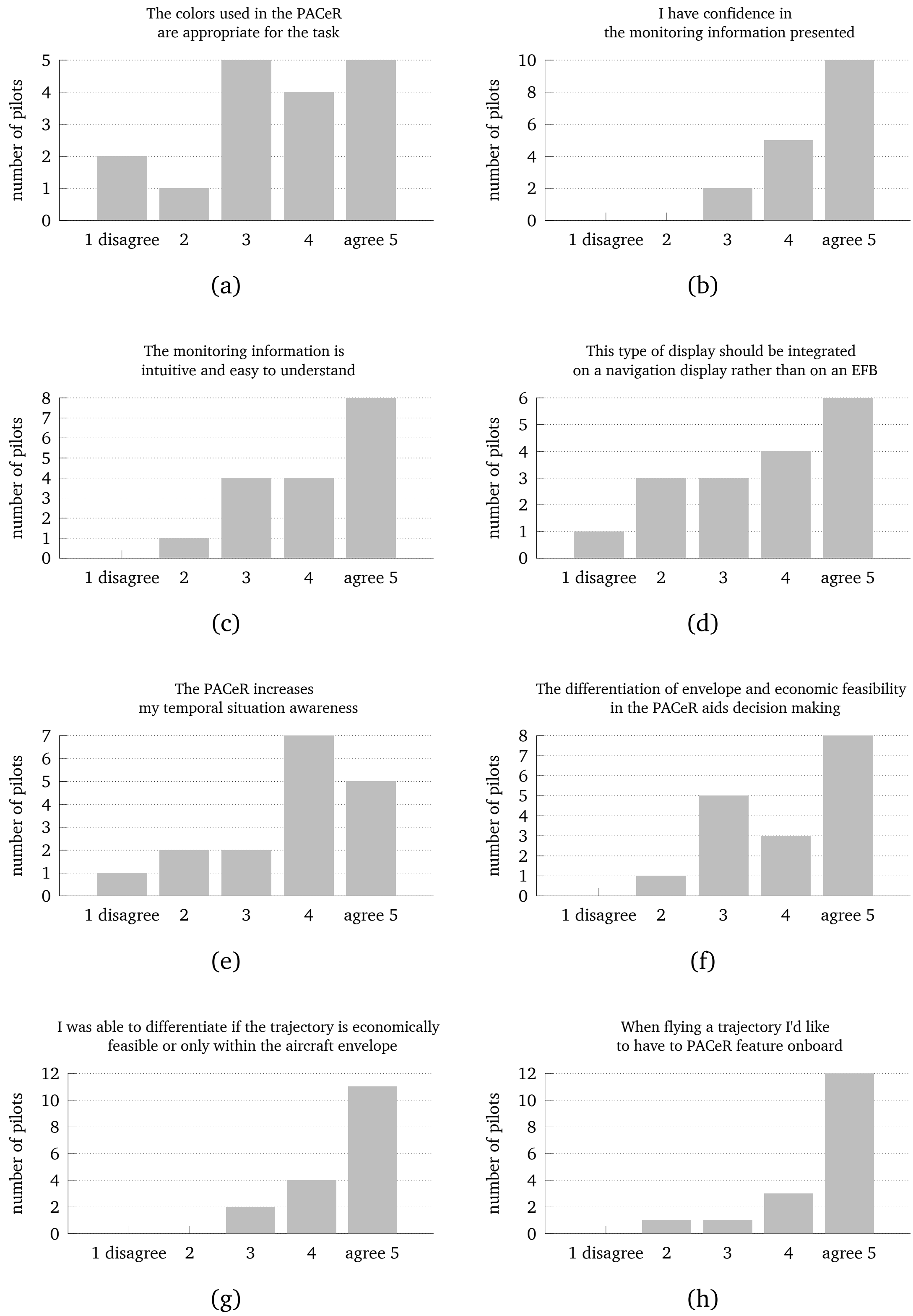


Figure D.6.: Monitoring ratings

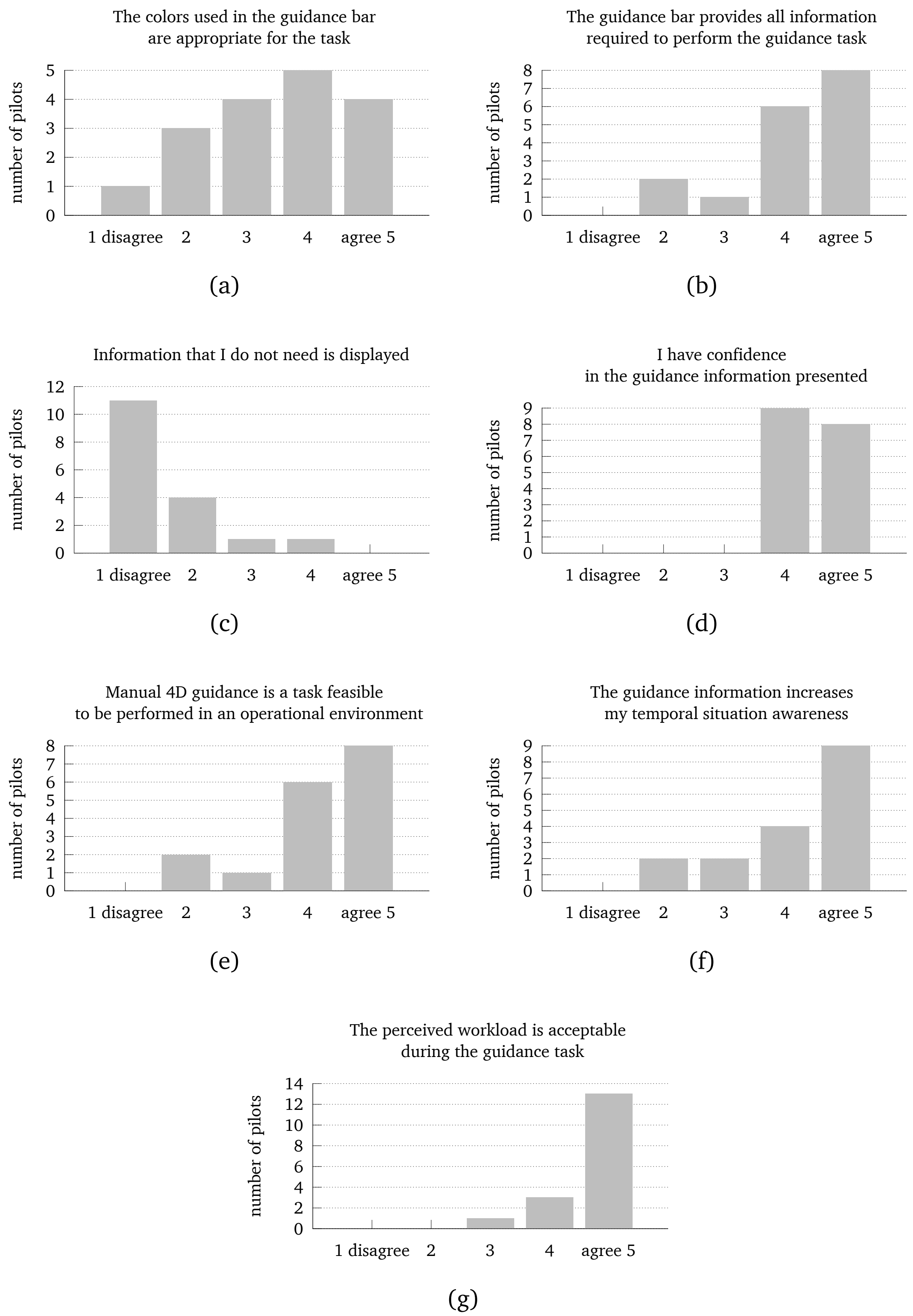


Figure D.7.: Guidance ratings

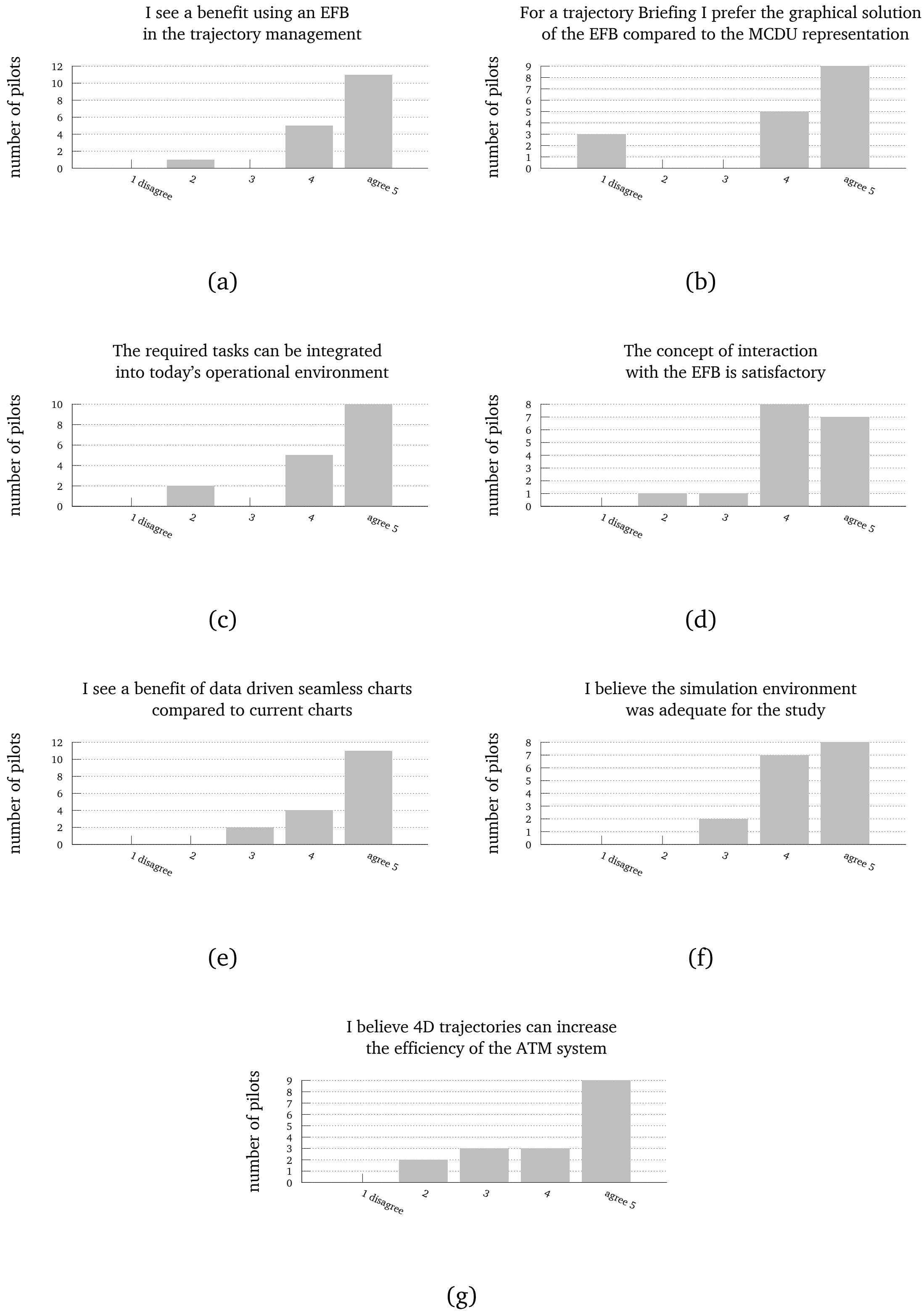


Figure D.8.: General ratings

E Test flight data

This Appendix provides additional data to that presented in Chapter 6 for the test flights and simulator trials of both the Boeing ecoDemonstrator and the DLR HETEREX flights.

E.1 Boeing ecoDemonstrator flight

Test flights were conducted with the Boeing ecoDemonstrator using the CDA-MP. The flight trials were accompanied by previous simulator trials to prepare the system and train the pilots. Data on both the simulator trials and test flight are presented in the following.

E.1.1 Data from simulator trials

To prepare the system and brief the pilots for the actual test flight, a series of simulator runs using the CDA-MP trajectory management and guidance system were conducted in Seattle using the Boeing B737 e-Cab high fidelity simulator. In total, ten simulator runs were performed to train the pilots and test the system performance. System integration was already tested previously in the Boeing R-Cab simulator. As the results from all simulator runs looked similar one was selected randomly to be discussed in the following.

In the simulator, the HAYS Military Operations Area (MOA) did not create a problem for an uninterrupted descent (compare Section 6.1.2), therefore a more direct routing was chosen from LWT directly to the Initial Approach Fix (IAF) D266W. The lateral routing is illustrated in Figure E.1 with the planned trajectory in red and the actual flown trajectory in black.

The test started in cruise altitude end ended when passing through an altitude of 10,000 ft Above Ground Level (AGL). Figure E.1[1] shows in top the altitude relative to cruise altitude of the aircraft over the distance from guidance start (TrajStart). In light gray, a phase with a vertical speed cue of -1,300 ft/min is indicated. In the second graph, the speed cue (in black) and the actual Indicated Airspeed (IAS) (in gray) are shown relative to the nominal descent speed. In the third graph, the time deviation relative to the maximum time deviation of the descent is shown. The higher speed at approximately 95 NM after start influences the time deviation as the time deviation decreases to nominal level. The effect of the vertical speed cue on the altitude deviation is illustrated in the fourth graph as it reduces the deviation to zero. A correlation between the relative speed deviation shown in the last plot in Figure E.2 and the relative time deviation can be seen.

[1] Compare to Figure 6.4 of the ecoDemonstrator flight.

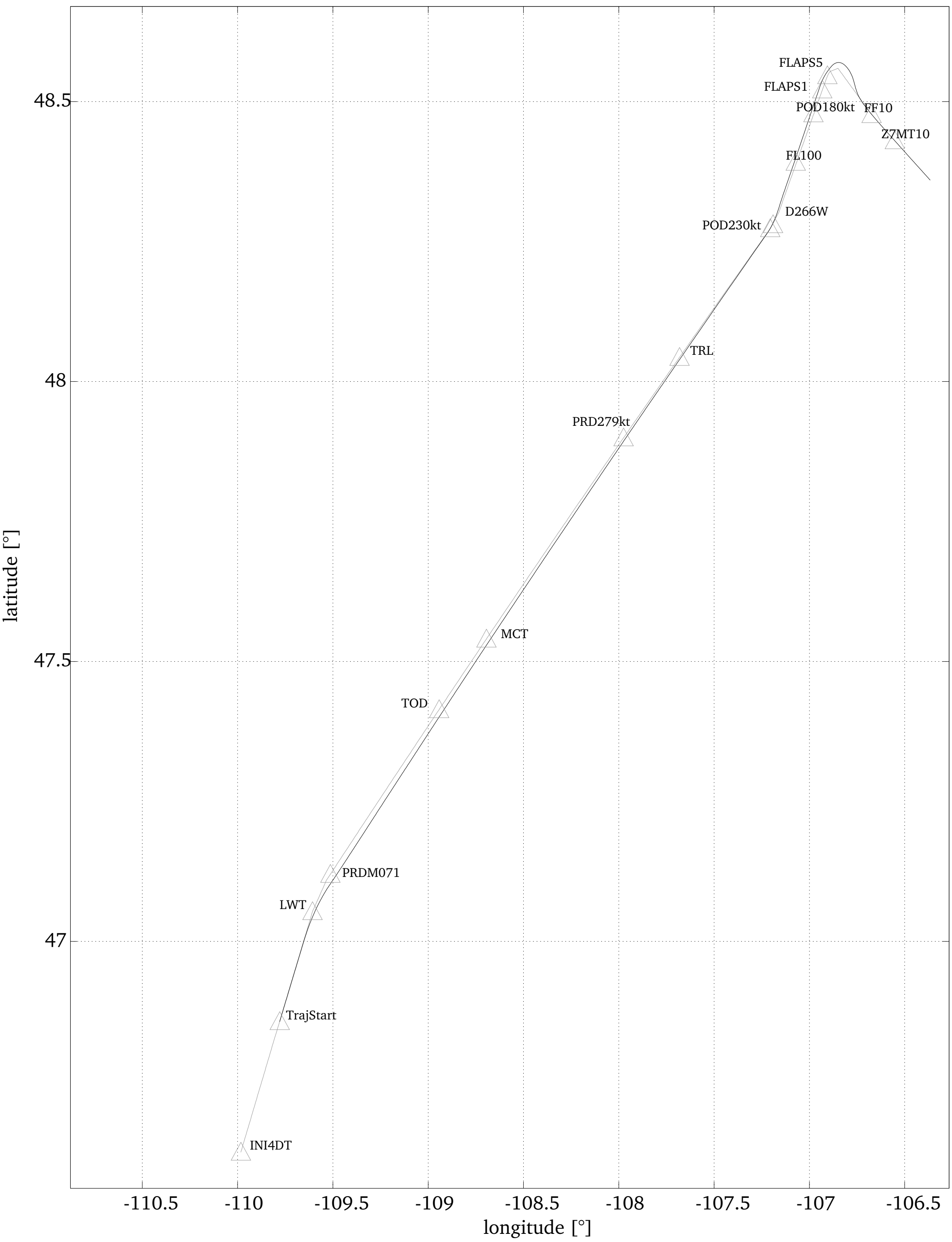


Figure E.1.: Lateral profile e-Cab simulator run

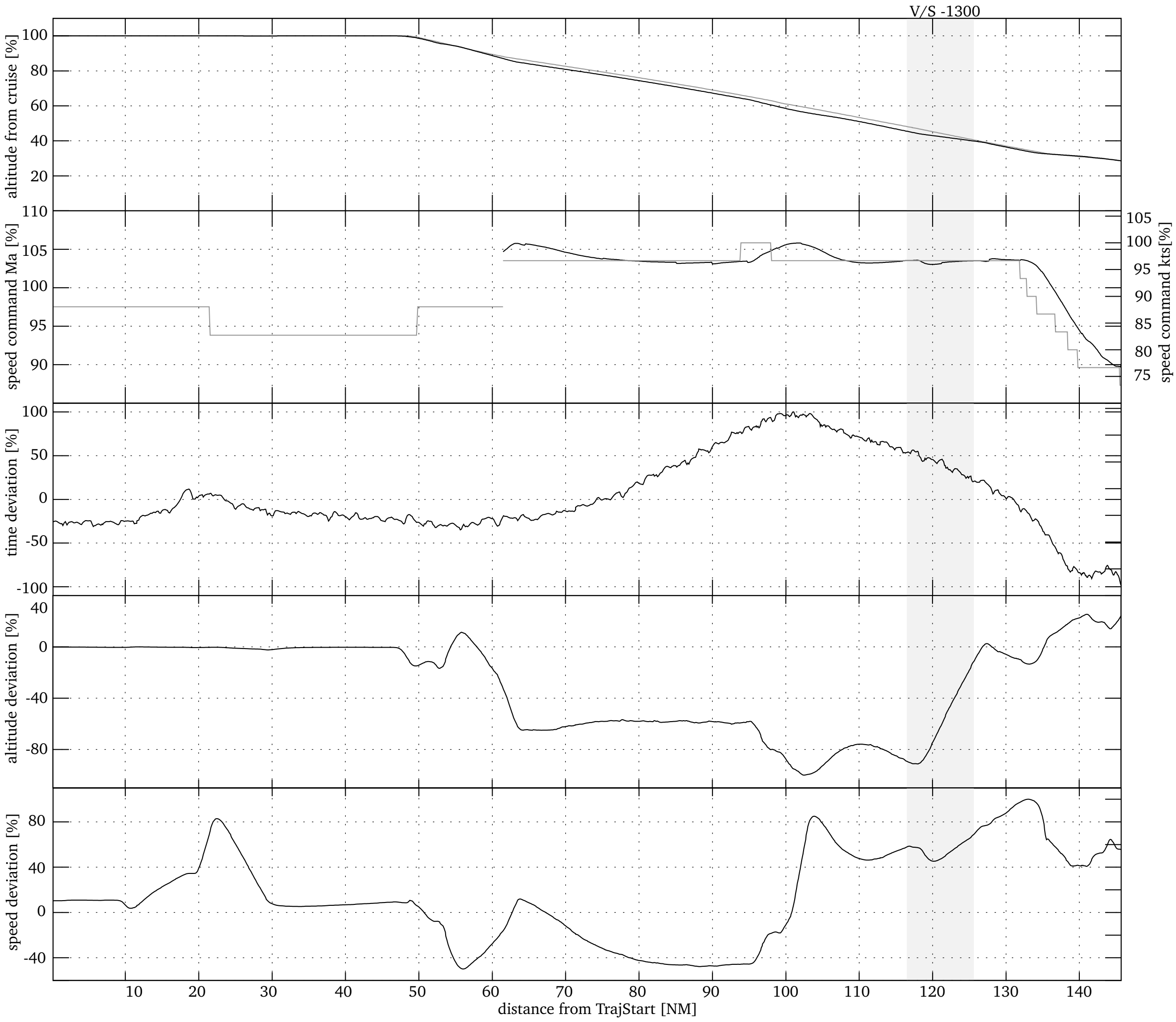


Figure E.2.: Altitude, speed command and actual and time, altitude, speed deviation for e-Cab simulator run

E.1.2 Data from flight trials

The following Section provides additional data of the ecoDemonstrator flight, an overview of the architecture, flown lateral profile, and an approach chart to Runway (Rwy) 10 in Glasgow Industrial Airport, MT, ICAO-Code (07MT).

The communication architecture of the ground and airborne systems for trajectory negotiation, calculation and guidance is detailed in Figure E.3. It provides an overview of the data flow and involved processes.

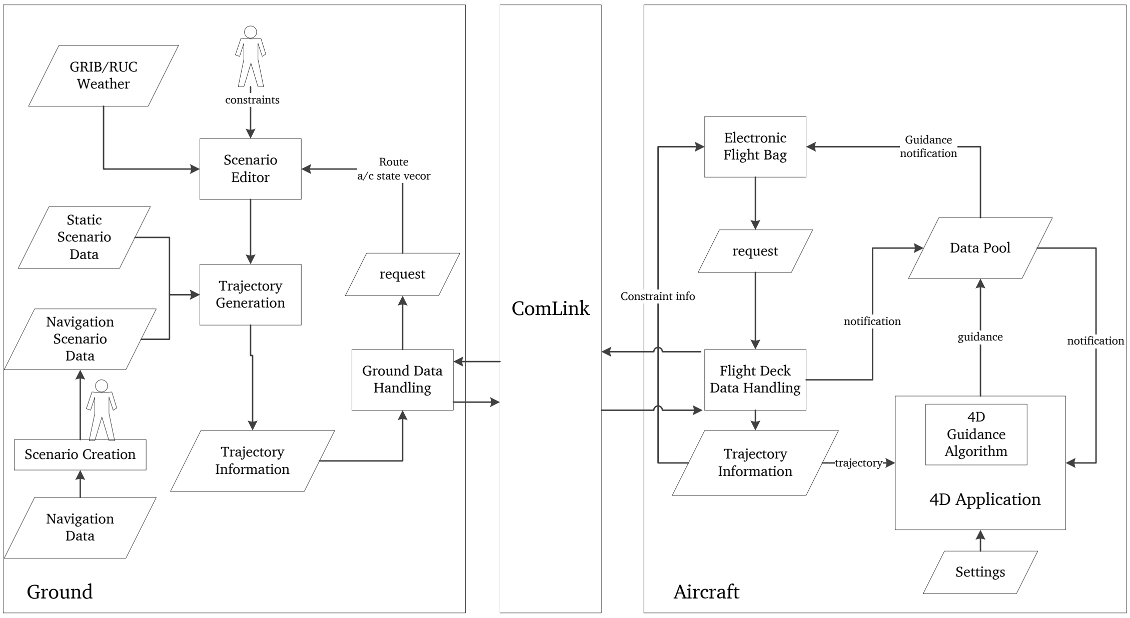


Figure E.3.: CDA-MP architecture [WKS12]

In Figure E.4 the lateral profile of the planned (pre-canned) trajectory in gray, and the actual flown trajectory in black, is shown together with the navigation and operational waypoints loaded into the G2G application. The actual trajectory path starts much later than the planned trajectory. Also interesting to note is the difference in turning radii of the fly-by waypoints. This difference between planned and actual flown lateral trajectory decreases the predictability of the time adherence of the trajectory, as it varies the flown distance.

The approach procedure shown in Figure E.5 is a custom approach designed by Jeppesen in 1994 for Boeing that owns and operates the airport at 07MT.

E.2 DLR HETEREX flights

The DLR HETEREX flight trial campaign consisted of simulator trials in the DLR Generic Experimental Cockpit Simulator (GECO) and flight trials onboard the DLR Advanced Technology Research Aircraft (ATRA) around the Hannover-Langenhagen, Germany, ICAO-

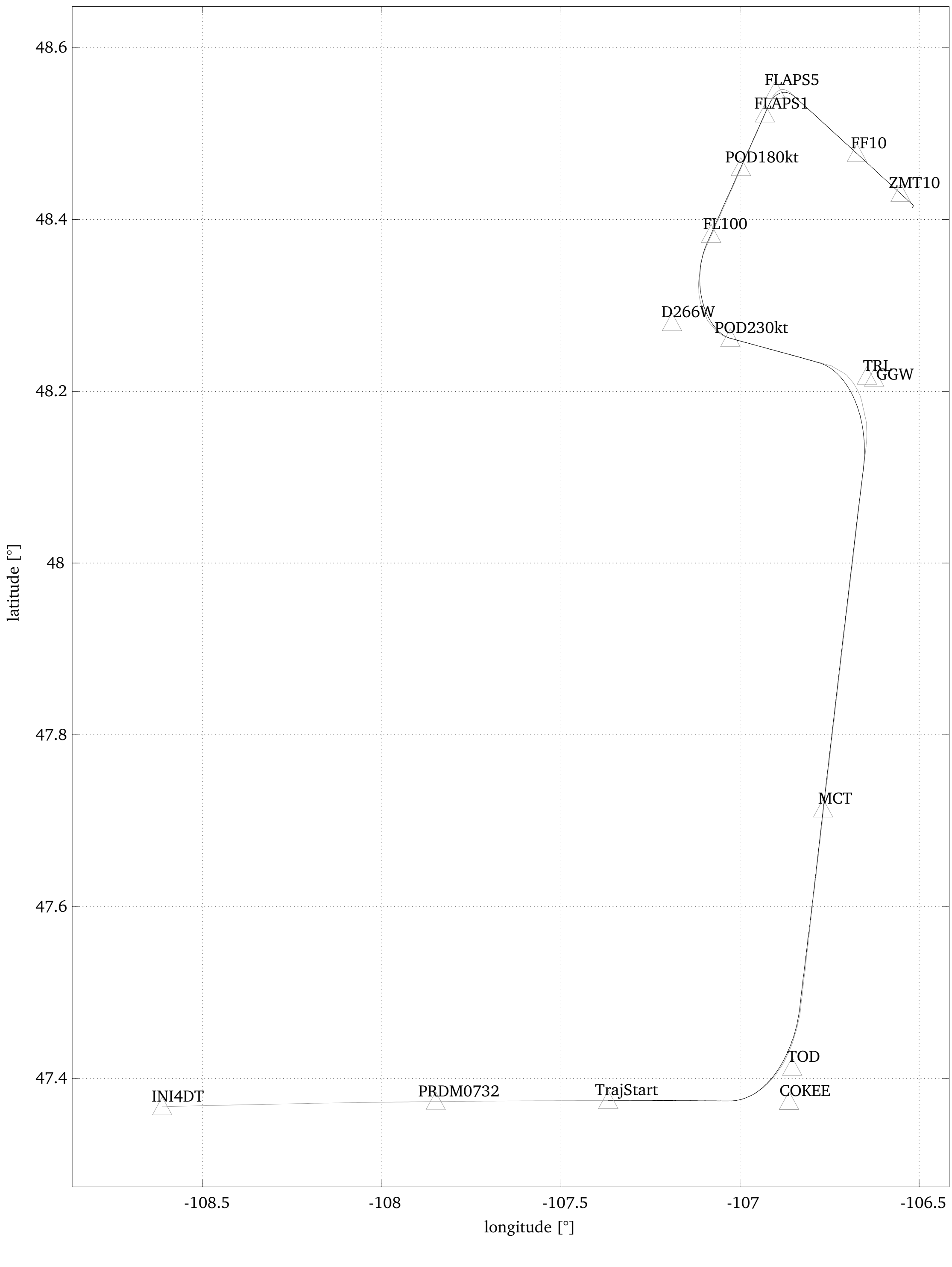


Figure E.4.: Lateral profile of CDA-MP flight, planned (red) and actual (blue)

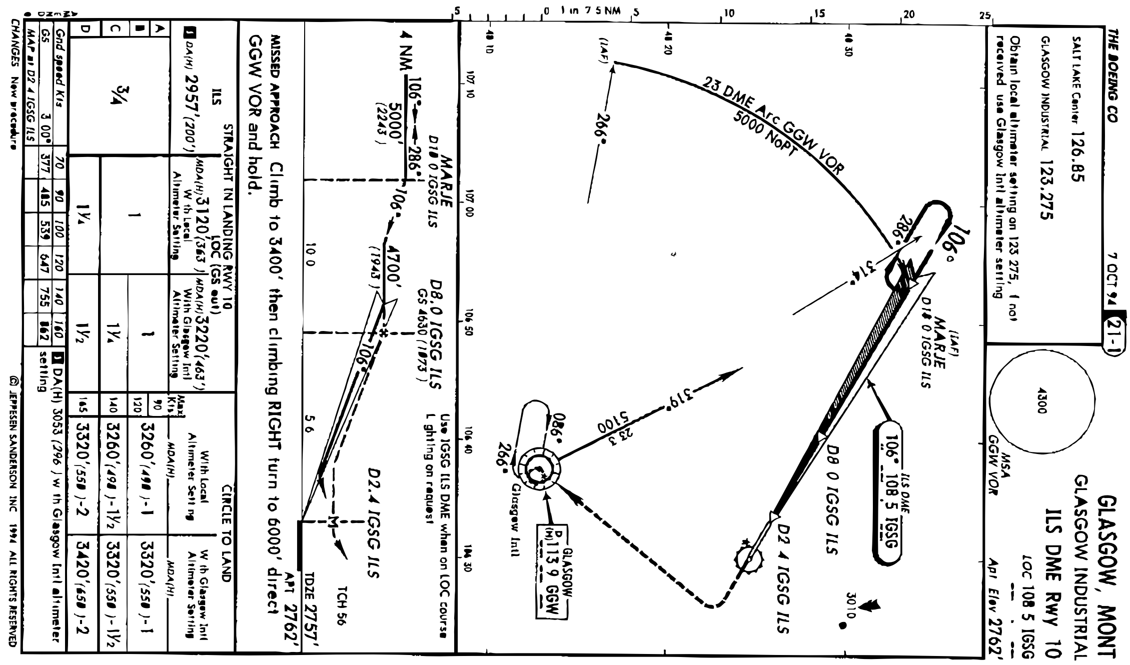


Figure E.5.: Approach chart 07MT ILS Rwy 10

Code (EDDV) Terminal Control Area (TCA). The trials were documented in reports from the HETEREX project. A detailed use case description presents an overview of how EDDV was chosen to be examined [PPM+12], and the report on the EDDV flight trials provides a comprehensive analysis of the performed flights [GW13]. All efforts leading to the flight trials are summarized in the final reports of the project [VFfLuR+13, WS13]. The following section provides additional data from these reports on the simulator and flight trials is presented.

E.2.1 Data from simulator trials

Simulator trials were conducted in the DLR GECO to prepare the developed system for the flight trials and to brief the pilots to the system and gather pilot feedback in an undisturbed environment. The system was integrated into the GECO depicted in Figure E.7(b) on NavAero Electronic Flight Bag (EFB) hardware as shown in Figure E.7(a). In the simulator trials the 4D Required Navigation Performance (RNP) approach was compared to the Area Navigation (RNAV) performance in flight time and fuel consumption. The results for various waypoints enroute is presented in Table E.1. The GECO integration had the advantage over the ATRA integration that a direct connection of the DLR FMS with the autopilot existed. This architecture is presented in Figure E.6. In Figure E.8, the altitude and Cross Track Error (XTE) are plotted for both the RNAV and RNP approach into EDDV. The plotted approaches were recorded during a training session for the pilots. In this case, the autopilot was not directly connected to the FMS. This explains the large XTE

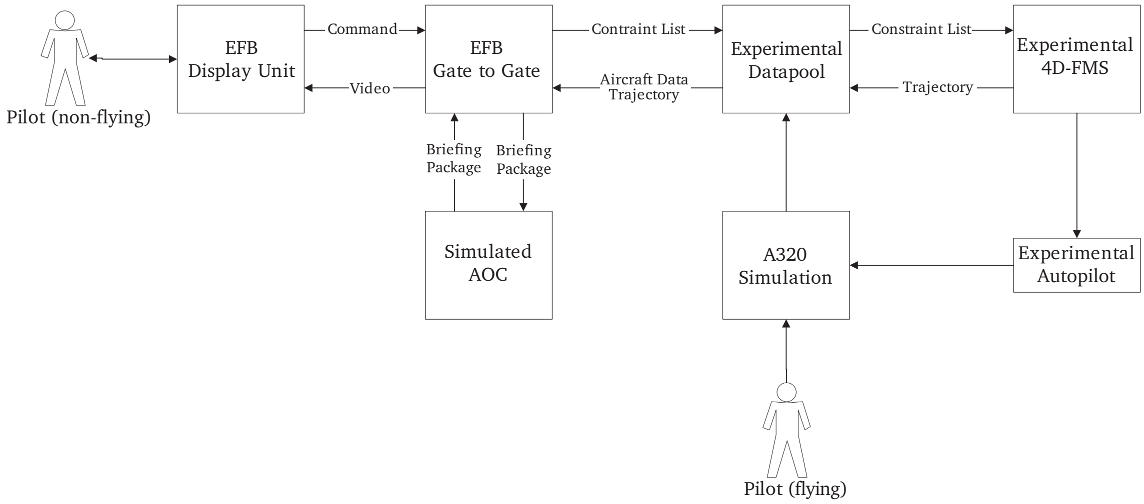


Figure E.6.: Architecture of systems in GECO [GW13]

when passing VISKI. The trial was performed with no wind setup in the simulator. The result was slight time deviations during the flight as shown in Figure E.9, where temporal flexibility and time deviation are plotted for the flight RNP approach. The approach was constrained by ten-second time windows at OSN and VISKI. Once the Final Approach Fix (FAF) is reached and speed is only adjusted by procedural control, a large time deviation occurs because of an inaccurate modeling of the trajectory prediction during this phase.

Table E.1.: Fuel consumption and flight time for RNP and RNAV approach in GECO [GW13]

waypoint	fuel used RNP	fuel used RNAV	difference fuel used	flight time RNP	flight time RNAV	difference flight time
VISKI	119.6 kg	172.3 kg	52.7 kg (30.6%)	798 s	968 s	170 s
OSN	193.8 kg	254.5 kg	60.7 kg (23.9%)	1062 s	1204 s	142 s
BADMU	257.2 kg	330.5 kg	73.3 kg (22.2%)	1285 s	1399 s	114 s
ROBEG	290.5 kg	370 kg	79.5 kg (21.5%)	1401 s	1507 s	106 s

E.2.2 Data from flight trials

The Section presents additional data to that from Section 6.2 of the HETEREX flight trials. Table E.2 shows a comparison of the fuel consumption and flight time for the 4D RNP and the RNAV approach into EDDV for various waypoints enroute. The savings were slightly lower than expected from the simulator trials. This savings is likely the result of an inaccurate fuel burn model in the simulator, and differing wind conditions.

The tasks of both pilots and their interaction with the system is depicted in the system architecture in Figure E.10. In comparison to the GECO integration, the pilot flying has to

(a) NavAero EFB

(b) GECO simulator during trials

Figure E.7.: Hardware integration for HETEREX simulator trials

Table E.2.: Fuel consumption and flight time for RNP and RNAV approach in ATRA [GW13]

waypoint	fuel used RNP	fuel used RNAV	difference fuel used	flight time RNP	flight time RNAV	difference flight time
VISKI	131.6 kg	170.0 kg	38.4 kg (22.6%)	840 s	965 s	125 s
OSN	212.4 kg	264.5 kg	52.1 kg (19.7%)	1163 s	1227 s	64 s
BADMU	287.1 kg	345.6 kg	58.5 kg (16.9%)	1395 s	1452 s	57 s
ROBEG	327.2 kg	384.8 kg	57.6 kg (15%)	1517 s	1567 s	50 s

manually follow the guidance cues and the connection to the AOC has to be established via data link.

The zoomed-in plot shows both the RNP in red with the one RNP protection zone in gray and the RNAV trajectory in blue in Figure E.12. At the end of the Radius to Fix (RF) turn of the RNP approach, deviations of the flown RNP procedure compared to the procedure design occured. These deviations derive from a non-Aeronautical Radio Incorporated (ARINC) 424 [Aer11] compliant turn description in the DLR FMS. However, the pilot-flying managed to keep XTE to the planned trajectory within the limits of RNP 0.3 (555.6 m), as shown in Figure E.11, where the XTE is plotted for both the RNP and RNAV approach.

In the following, all terminal procedures used during the simulator and flight trials are presented. The flight started either on the Leine, VOR (DLE) 6T or DLE 7U departure from Braunschweig-Wolfsburg, Germany, ICAO-Code (EDVE) presented in Figure E.17. The approach into EDDV was either flown on the developed RNP procedure (shown in Figure E.15) or the RNAV transition VIS 1D (shown in Figure E.16) for west wind condi-

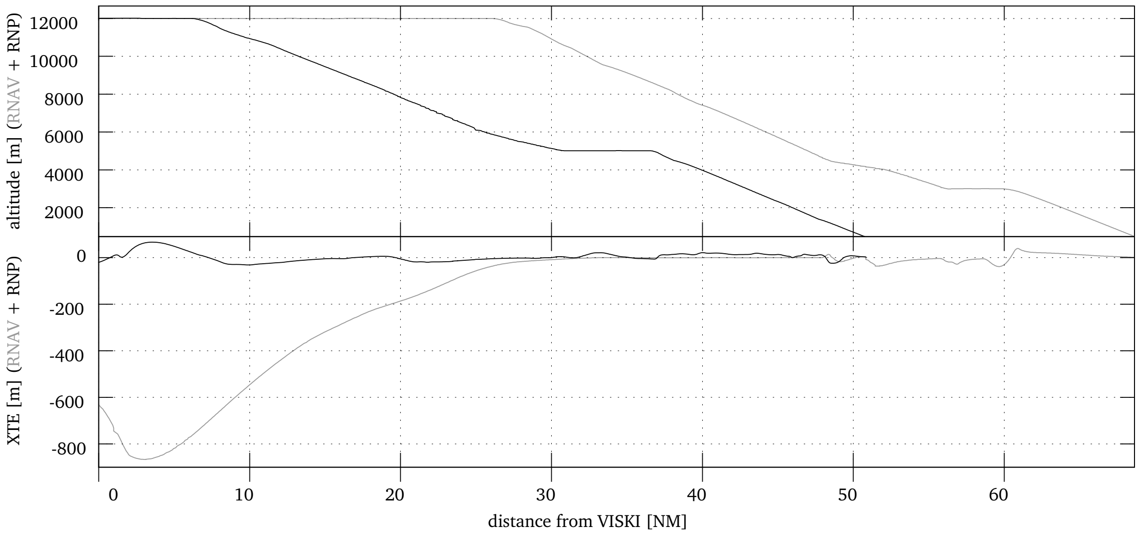


Figure E.8.: XTE and altitude for RNAV and RNP approach into EDDV in GECO [GW13]

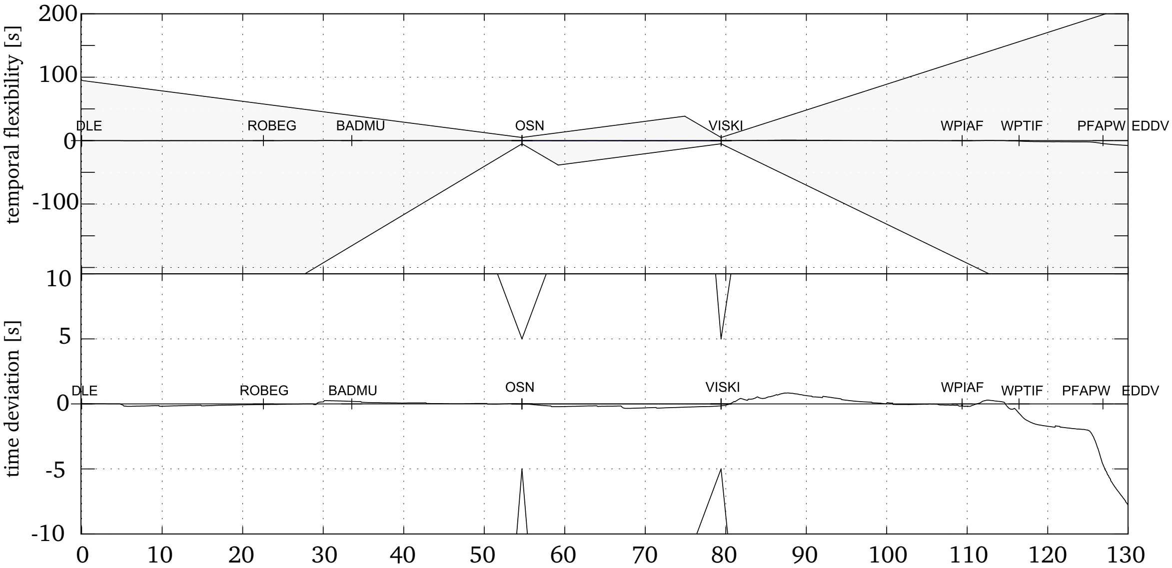


Figure E.9.: Temporal flexibility and time deviation for the RNP approach into EDDV in GECO tions and KUGAV 1A (shown in Figure E.20) for east wind conditions. The departure in EDDV took place on the POVEL 1F or 1Y Standard Instrument Departure (SID) (shown in Figure E.18) depending on the wind conditions, in addition it was planned on the RNP SID developed for the flight trials (shown in Figure E.19). Not included are the Standard Terminal Arrival Route (STAR) and approach charts for EDVE where G2G served as paper chart replacement only.

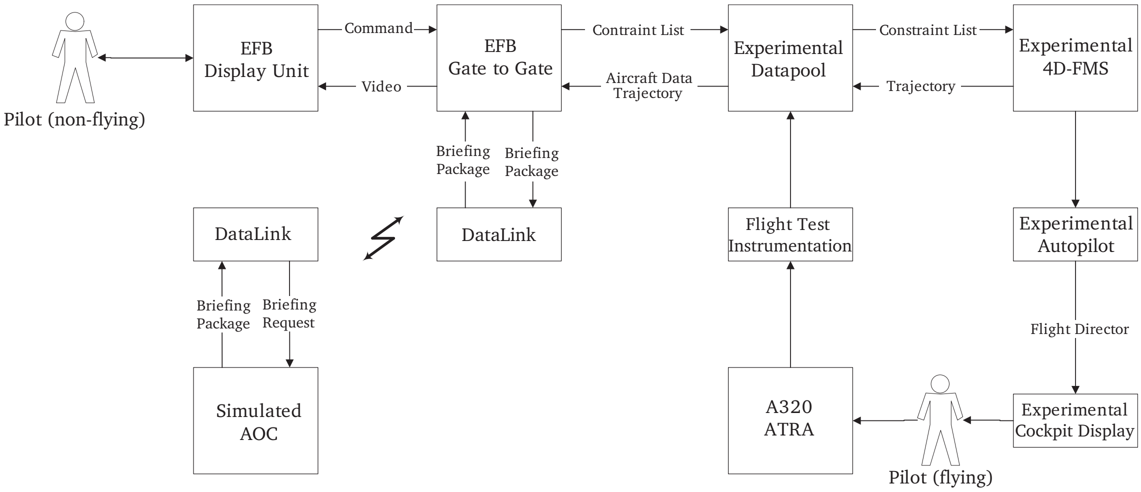


Figure E.10.: Architecture of systems in ATRA [GW13]

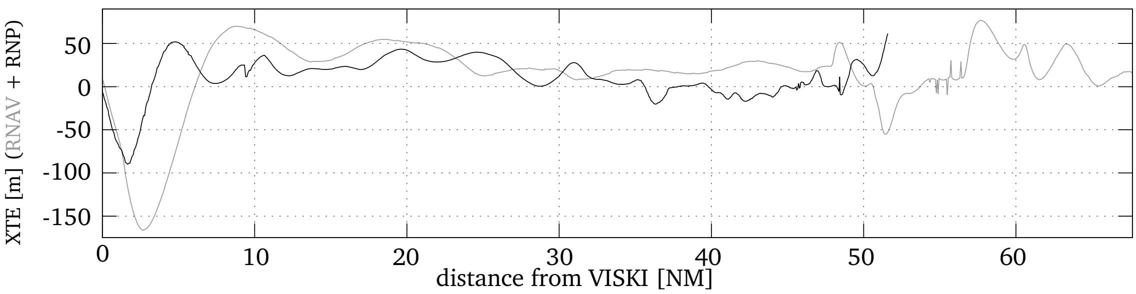


Figure E.11.: XTE for RNAV and RNP approach into EDDV in ATRA [GW13]

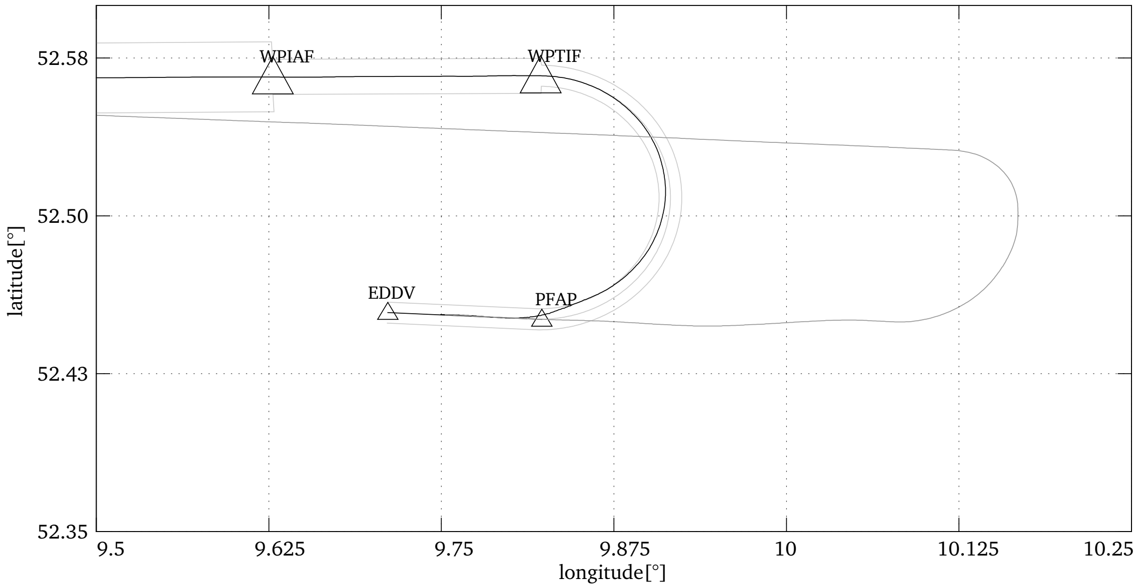


Figure E.12.: Lateral profile for RNAV and RNP approach into EDDV in ATRA [GW13]

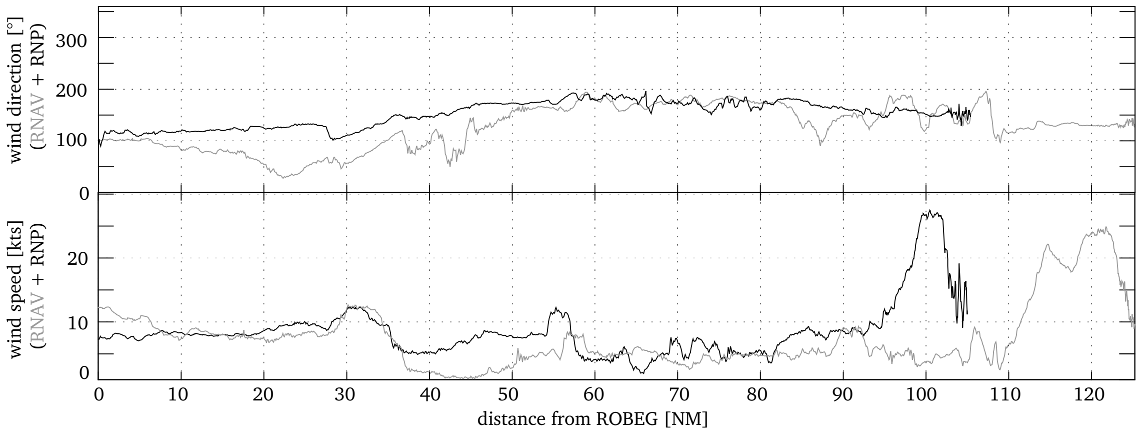


Figure E.13.: Wind speed and direction for RNAV and RNP approach into EDDV in ATRA

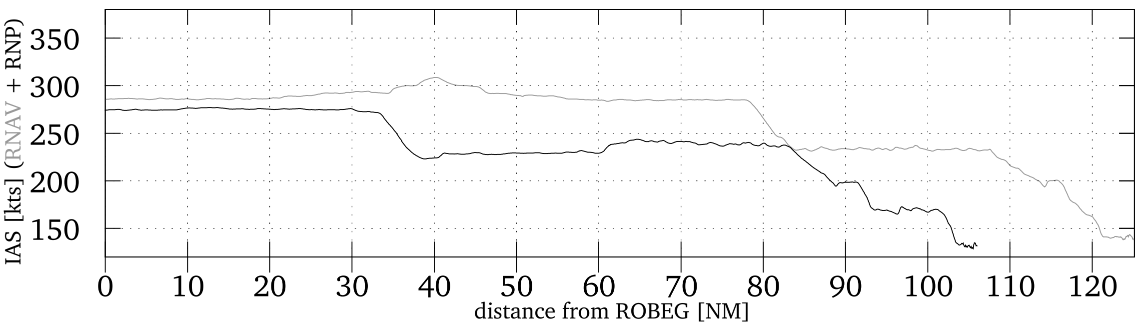


Figure E.14.: IAS for RNAV and RNP approach into EDDV in ATRA [GW13]

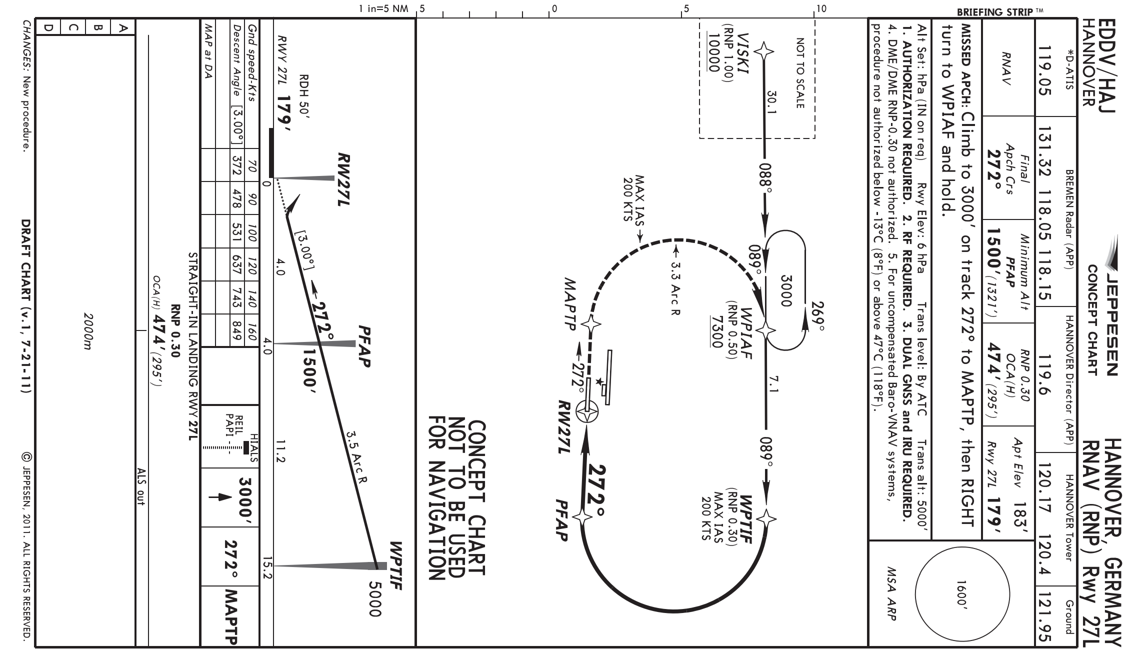


Figure E.15.: RNP approach EDDV Rwy 27L

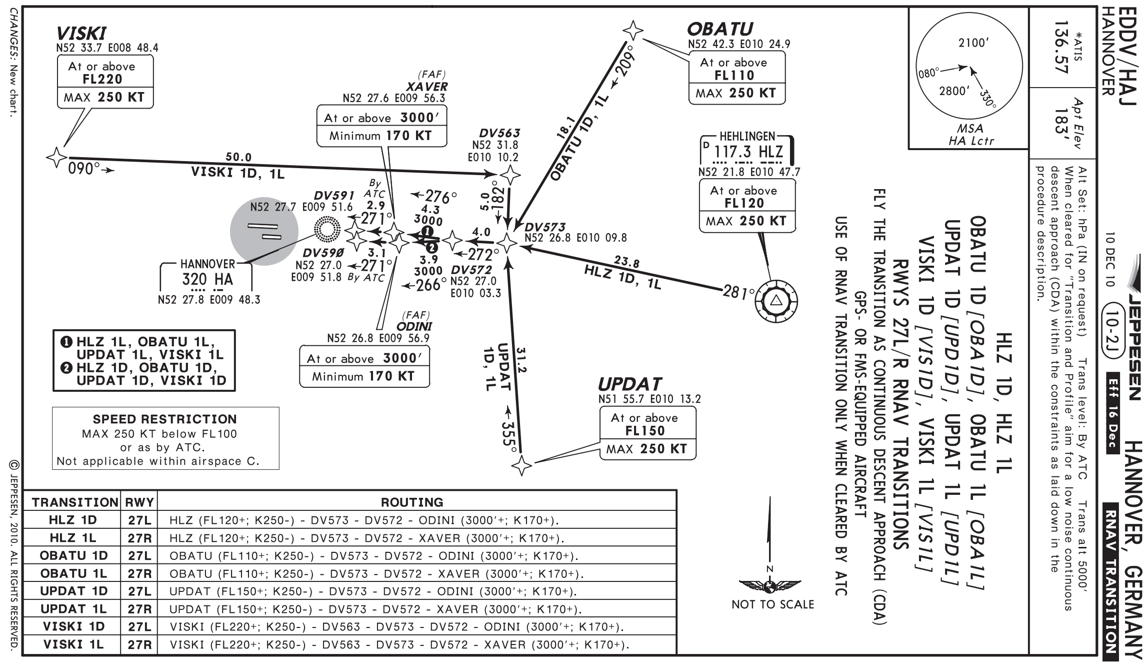


Figure E.16.: VISKI 1D RNAV transition

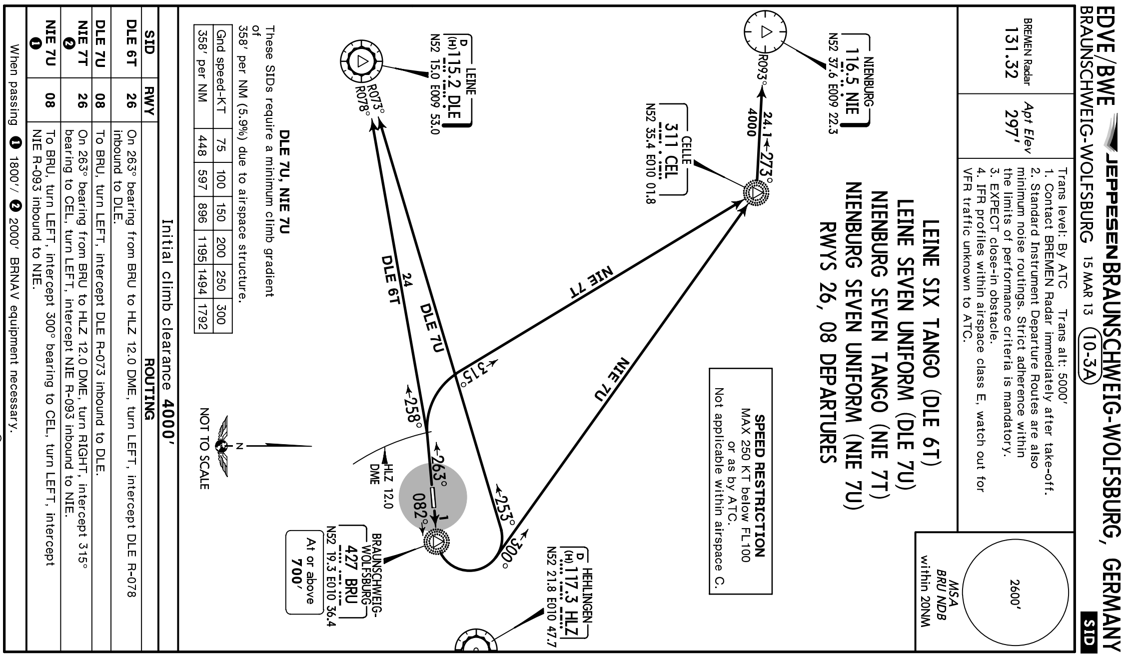


Figure E.17.: DLE 6T and DLE 7U SIDs EDVE

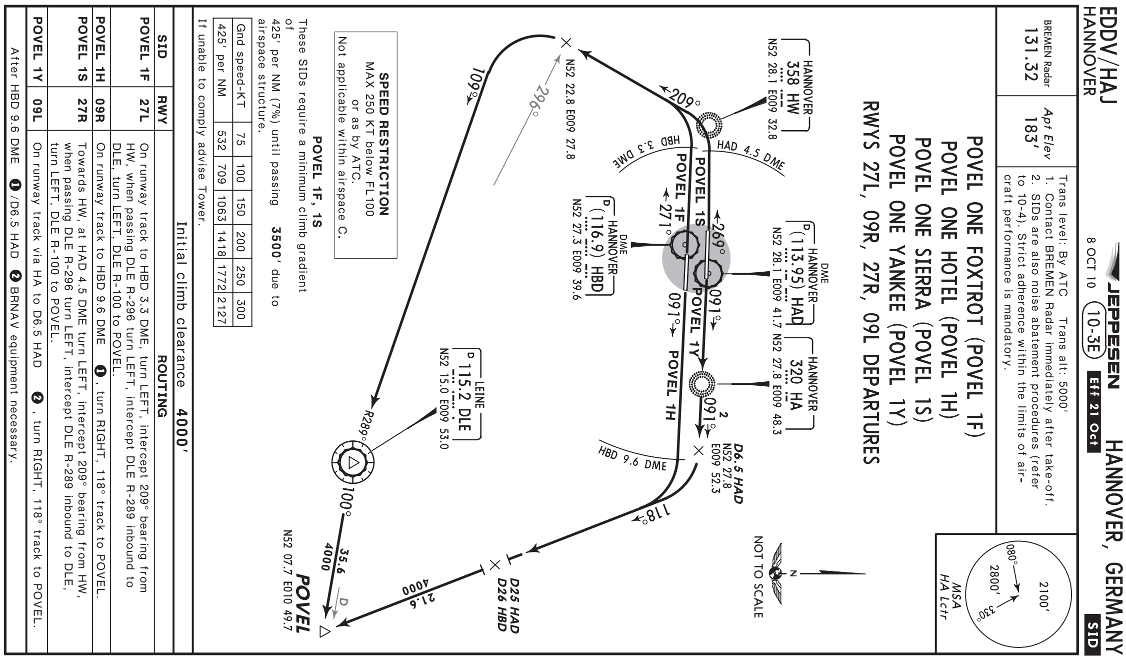


Figure E.18.: Povel 1F and Povel 1Y SIDs EDDV

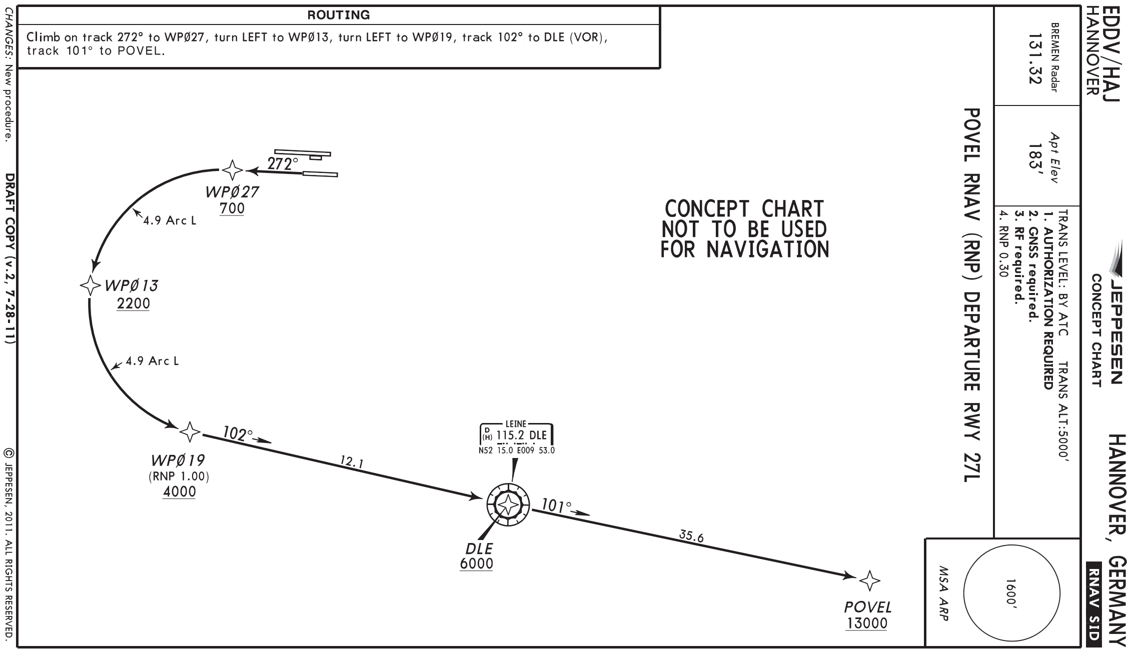


Figure E.19.: HETEREX RNP departure EDDV

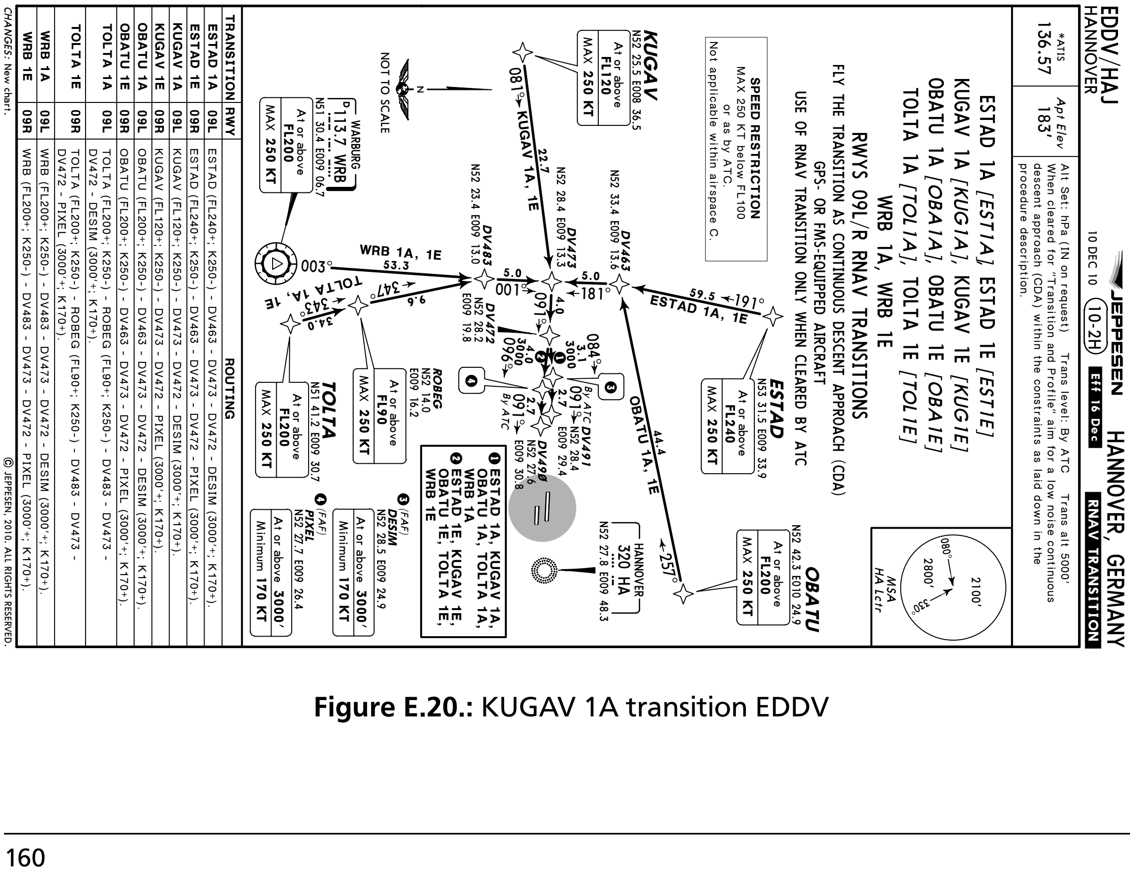


Figure E.20.: KUGAV 1A transition EDDV

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Experience

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02/2011 - 05/2014	Research Associate at the Institute of Flight Systems and Automatic Control of the Technische Universität Darmstadt
01/2010 - 10/2010	Intern at Jeppesen GmbH, Neu-Isenburg
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Education

10/2005 - 10/2010	Mechanical Engineering at the Technische Universität Braunschweig Degree: *Diplom-Ingenieur*
08/1996 - 06/2005	Gymnasium Dörpsweg, Hamburg Degree: *Abitur*

Selected publications

2013 **J. Westphal, N. Barraci, U. Klingauf and J. Schiefele.** *Transforming Time - towards an intuitive time constraint depiction.* In 3rd International Conference on Application and Theory of Automation in Command and Control Systems (ATACCS), Naples, May 2013

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